VOLTAGE SECURITY AND LOSS MINIMIZATION STUDIES IN ELECTRIC POWER SYSTEMS

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By

Sri Niwas Singh

to the

DEPARTMENT OF ELECTRICAL ENGINEERING

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APRIL, 1995

dedicated

to

my Parents

Certificate

It is certified that the work contained in the thesis entitled **VOLTAGE SECURITY AND LOSS MINIMIZATION STUDIES IN ELECTRIC POWER SYSTEMS,** by *Sri Niwas Singh* has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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THESIS SUPERVISORS

During the initial period from January 2, 1991 to April 29, 1994, this work for the award of the Ph.D. degree submitted by Mr. Sri Niwas Singh was carried out under the co-supervision of Prof. S.C. Srivastava and Prof. P.K. Kalra. Thereafter, Prof. S.C. Srivastava served as the sole supervisor.

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Synopsis

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Power system security has been defined as the ability of the system to meet its load without unduly stressing its apparatus or allowing network variables to stray from prescribed range. Voltage security has recently gained importance due to stressed operation of power systems. To assess voltage security of a system, operating limits of bus voltage magnitudes and reactive power output of sources are checked for various contingency cases.

Two major functions of power system security are *security assessment* and *security control*. The security assessment involves contingency analysis, which can be performed by AC load flow for various outage cases. However, the number of contingencies in a practical system is so large that they can not be analyzed on-line by AC load flow methods. In order to reduce the computational time, the contingencies are first ranked in rough order of their relative severity employing contingency selection algorithms. Then full AC load flow is run for only severe contingency cases. Contingency selection algorithm requires some fast methods, which may be approximate, to assess the system states following each outage.

Most of the works on voltage contingency selection have attempted use of approximate methods such as local solution method, one iteration of AC load flow, the linearized load flow models [2,9] and the distribution factors [8]. Existing models of these methods, in general, provide results with large errors and many of them are based on unrealistic assumptions. The distribution factor method suggested in reference [8] is based on decoupling assumption which may not be applicable in heavily stressed condition of power systems [12].

In order to assess the relative severity of the contingencies, scalar performance indices [1] have been used. Two typical problems with the performance indices are the masking and misranking effects. To avoid the misranking, the proper selection of weights for voltage and reactive power performance indices can be utilized. One attempt to use optimal weights in the performance indices is by Halpin et al. [4] who have utilized a probability based model.

After performing the security assessment, if the system is found to be in *insecure state,* security controls are exercised in order to bring the system into *secure state.* It can be achieved by corrective rescheduling or by running security constrained optimal power flow, provided the available controls in the system are capable of overcoming the system insecurity. Most of the works on optimal power flow uses the minimization of fuel cost of the fossil units and/or system transmission loss as objective [7]. However, cost characteristics of generating units may not be available with certain utilities. Hence, optimal power flow can not be formulated on cost criteria. Such utilities also need some guidelines to optimally adjust the real and reactive power outputs of sources. One possible criteria to allocate the optimal settings of both the real and reactive power outputs of sources, can be the minimization of the system transmission loss. This may also help in enhancing the load delivery capacity of those utilities which are facing shortage of power.

For solving optimal power flow, the conventional methods include the classical coordination method, linear programming, quadratic and Newton's methods etc. However, these methods, in general, require close initial guess of variables and suffer from the convergence difficulties and local optima. Genetic algorithm (GA) [6] is becoming popular due to its robustness in finding near optimal solution. GA works on coding of parameters instead of their actual values and uses multiple path search along with probabilistic transition rule in parameter space. It has been applied to some of the power system problems and is yet to be tried for the solution of complete optimal power flow problem.

Conventional security constrained optimal power flow considers the contingency constraints to the optimal power flow problem which leads to the implementation of preventive control action. Though, this formulation may ensure a higher level of system security, but reduces the economic benefit of the optimal operation. In order to maximize the economic benefit of optimal power flow, system operation in *correctively secure state* has been suggested [5]. Base case optimal power flow results are not modified for the contingency cases. The corrective actions for each of the contingencies are planned, in advance, with the help of optimal power flows. However, sometimes, it may not be feasible to bring the system to normal state with available controls, specially following the severe contingencies. This leads to infeasibility of the optimal power flows. Very few works have been reported to handle infeasibility of optimal power flow or divergent power flow cases [3, 10, 11]. The corrective action planning to solve infeasibility of optimal power flow has been attempted in reference [3] by adding fictitious reactive power sources at problematic buses.

Therefore, the motivations behind the work reported in this thesis are:

(i) To develop more accurate models of linearized load flow suitable for predicting the bus voltages which can be utilized for voltage security assessment.

(ii) To explore new set of distribution factors to directly compute post-outage voltages and reactive power output of the sources following the outage of a transmission branch or a generator.

(iii) To explore new higher order voltage and reactive power performance indices in order to eliminate the masking effects and a method for selection of optimal weights of the performance indices to eliminate the misranking problem.

(iv) To develop a new optimal power flow model, considering system transmission loss minimization as an objective, to determine the optimal settings of the real and reactive power outputs of the sources and apply the genetic algorithm for its solution.

(v) To suggest a method based on eigenvalue analysis for planning corrective controls in order to enhance the system voltage/reactive power security and to eliminate the infeasibility of optimal power flow problem.

A brief description of the work reported in the thesis is given below:

Chapter 1 introduces the power system security and optimal power flow problems, presents a brief state-of-art survey on the subject and sets the motivation behind the research work carried out in the thesis.

In Chapter 2, six different models of new linearized load flows for voltage security analysis have been developed based on the principle of linearizing non-linear power flow equations (in both polar and rectangular coordinates) around complete operating range using the least square error and integral square error minimization principles.

Chapter 3 presents the developments of new set of distribution factors which have been computed using the sensitivity property of Newton-Raphson load flow Jacobian at a base operating point. These have been used to calculate the post-outage voltages and reactive power output of the sources following the outages of both transmission branches and generators.

Chapter 4 investigates few higher order voltage and reactive power performance indices to remove masking effect. In order to avoid the misranking effect, a new procedure to compute the optimal weights has been suggested.

Chapter 5 formulates the optimal power flow problem having objective of system transmission loss minimization to obtain optimal scheduling of both real and reactive power output of sources. The genetic algorithm has been used to solve the loss minimization problem and results have been compared with Flechter's quadratic programming technique.

Chapter 6 presents the development of a method for corrective action planning which determines the controls to enhance the voltage/reactive power security. The left eigenvector corresponding to the minimum eigenvalue of reduced power flow Jacobian has been utilized to compute the corrective controls.

Chapter 7 highlights the main findings of the thesis and identifies the scope for future research in this area.

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Sri Niwas Singh

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 General

With ever-increasing interconnections and loading in the modern power system networks, all over the world, power utilities are facing a major challenge in maintaining desired security of power supply. An operationally secure power system is one with low probability of black out or equipment damage. *Security* is a term used to reflect a power system's ability to meet its load without unduly stressing its apparatus or allowing network variables to stray from prescribed range.

A power system runs under two sets of constraints viz. *load constraints* and *operating constraints*. The load constraints impose the requirements that all the loads be met and the operating constraints impose lower and upper limits on network variables. With these constraints, a three state model of power system security was first suggested by DyLiacco [1] in 1967. A system is said to be in *normal state* when both the load and operating constraints are met. The system is in *emergency state* when there are violations of operating constraints, though, the load constraints are satisfied. In *restorative state*, the system operating constraints are met but load constraints are not satisfied. Further detailed classification of power system states have been suggested by Fink and Carlsen [17] and Stott et al. [55].

The security is referred with respect to a certain prespecified *credible* contingencies. The contingencies are either in the form of *network outages* such as a line or transformer outage or in the form of *power outages* e.g. a generator outage. The quantities which are important from limit violation viewpoint are branch flows for *line security* or *MW security*

and bus voltage magnitudes for *voltage security.* This thesis has mainly considered the static voltage security problem which has also attracted the attention of researchers in the recent past.

The concept of security in system operation may be delineated into three components, namely, monitoring, assessment and control. *Security monitoring* starts with the measurements of real time system data to provide up-to-date information of the current condition of power system. *Security assessment* is the process whereby any violation of operating limits is detected. It has two functions. The first is the detection of violation of the actual system operating states. The second, much more demanding, function of security assessment is *contingency analysis* and normally performed into three distinct stages: *contingency definition, selection* and *evaluation.*

Contingency definition gives the list of contingencies to be processed whose probability of occurrence is high. *Contingency selection* employs an adaptive scheme to select a set of important and critical contingencies. It invariably uses an approximate power system model with appropriate computational techniques, to give relatively fast but results with limited accuracy. On the basis of these results, the contingency cases are ranked in rough order of their relative severities. *Contingency evaluation* using AC power flow is then performed on the contingency cases in decreasing order of severity. The process is continued up to the point where no post-contingency violations are encountered. In some cases, contingency selection and evaluation are merged into one process. A single set of simulation on contingency list can be performed when either :

(1) the accuracy of an approximate selection type model/solution is adequate throughout, or

(2) when fast selection cannot be performed reliably and more accurate evaluation type model/solution are needed throughout.

Security control or *security optimization* is concerned with the selection of control actions to prevent the violations or to minimize the impact of contingencies. It can be formulated as an *optimal power flow* (OPF) problem. The general OPF formulation involves the minimization of objective function(s) subject to specific operating constraints. Different classes of OPF problems for security control, tailored towards special purpose applications, are defined by selecting appropriate objective functions to be minimized along with the set of control variables and constraints.

For secure operation of the system, it is essential to modify the dispatch philosophy such that it ensures the normal operation of the system even under contingency cases. In some cases, the solution of OPF may not remain feasible with available controls, specially while considering the severe contingencies. To ensure the security of the system, it is important to plan for corrective control actions to bring the system back into normal state or in a feasible constrained region.

1.2 State of Art

The problem of security, as it pertains today, emerged in the wake of the 1965 northeast blackout in U.S. The most significant paper in the literature of security is that of DyLiacco on adaptive reliability [1]. In this paper, the system security was defined with respect to the operating states. The problem of security monitoring has been introduced as that of monitoring, the conditional transition of the system into an emergency state through contingency analysis.

On-line contingency analysis becomes difficult due to the conflict between the accuracy with which the power system is to be solved and the speed required to simulate all the contingencies. In order to speed up the contingency analysis process, contingency selection is performed. The methods for contingency selection broadly falls under two classes – *direct methods* and *indirect methods*. In general, *indirect methods* [18,24,46,82] are less accurate, but faster and selective than the *direct methods* [28,43,94]. The *direct method* assembles the appropriate severity indices using the individual monitored quantities (bus voltages, branch flows, reactive generation). This implies that these quantities have to be first calculated. In contrast, the indirect methods rely on explicit calculation of severity indices without evaluating the individual monitored quantities.

The knowledge of individual monitored quantities permits the calculation of severity indices of any desired complexity without significantly affecting the numerical performance of the direct methods. Therefore, over last few years, more attention has been paid to the direct methods. Direct contingency screening methods can be classified by the embedded modeling assumptions. Two distinct classes of methods can be identified :

- linear methods specially designed to screen contingencies for possible real power (branch MW overload) problem,

- non-linear methods designed to detect both the real and reactive power problem including voltage problems.

Much of the developments on contingency selection has been performed for the active power problems using DC power flow or some other linearized models. A review of MW ranking methods has been presented in reference [68]. For voltage contingency selection, a number of trends has emerged. The most important amongst them either attempt to localize the outage effects, or speed up the non-linear solution of entire system.

The concentric relaxation method of Zaborsky et al. [20] can be seen as the earliest localization attempt. The main idea behind the method is to solve a small portion of the system in the vicinity of the contingency while treating the remainder of the network as an infinite expanse. The area to be solved is concentrically expanded until the incremental voltage changes along the last solved tier of buses is not significantly affected by the inclusion of the additional tier of buses. This method suffers from unreliable convergence, lack of consistent criteria for selection of buses.

A modification of the original approach has used a fixed number of tiers for AC contingency selection as suggested by Lauby et al. [36]. They have compared three methods of contingency selection including a performance index (PI) method, a local solution method and a single iteration of the Stott - Alsac's fast decoupled load flow. The authors observed that PI method performs well in detecting wide spread and severe voltage problems. However, the PI method is not well suited for the detection of local problems. The local solution method has been reported to be well suited for selecting circuit outages.

Several attempts have been made at improving the solution efficiency specially for large systems. These can be classified as follows:

- attempts to speed up the solution by means of approximation and/or partial (incomplete) solutions [9,28,43]

- attempts to speed up the solution by means of using network equivalents (reduced network representation) [53,94].

The use of a partial (incomplete) solution became well established with the introduction of the single load flow iteration approach [28]. The main idea behind the method was to take advantage of the speed and reasonably fast convergence of the fast decoupled power flow by limiting the number of iterations to one. The single iteration approach has

been combined with other techniques like use of the reduced network representation [53] to improve numerical efficiency.

An alternative approach is based upon bounding of outage effects [72,82]. Similar to the bounding in linear contingency screening [56], an attempt to find the solution only in stressed areas of the system is made. A set of bounding quantities is built to identify buses which can partially have large reactive mismatches. The actual mismatches are then calculated and the forward solution is performed only for those buses with significant mismatches. The complete bounding method expanded the conventional set of limit violation severity indices by adding the severities of shifts from base case conditions.

Bacher et al. [80] presented a zero mismatch method which extends the application of localization ideas from contingency screening to full iterative simulation. The zero mismatch method is significantly different from the concentric relaxation approach. The main difference between the two methods is in the network representation. The zero mismatch method uses the complete network model while a small subsystem representation is used in latter one. The zero mismatch method is highly reliable and of acceptable accuracy.

Linearized load flow has been used for contingency analysis in view of speeding up the solution. Peterson et al. [9] have introduced an iterative linear AC power flow solution for fast approximate outage study using inverse matrix modification lemma (IMML). Albuyeh et al. [28] have proposed to use one iteration of fast decoupled load flow to compute voltage and reactive power.

Khu et al. [31] have reported fast non-iterative linearization method devised to evaluate the effects of single or multiple-circuit contingencies upon the system load bus voltages. The results of DC load flow techniques have been used to find linearized equation to compute the changes in load bus voltages due to the outage. The authors have also presented a method to calculate the reactive power change required to maintain scheduled voltage at generator buses. The method employs as many as eight assumptions and some of them are not practically justifiable.

Jana et al. [130] have presented an improved linearized method to evaluate load bus voltage magnitudes following a line outage. However, this method also involves some unrealistic assumptions such as the lines are assumed to be purely inductive, load bus voltages are not controlled by tap changing transformers and power injection at buses are assumed to be constant. Also the P-V and Q-δ decoupling assumption have been made which may not be valid, specially, in heavily stressed conditions of network [154].

Leonidopoloulos [105] has retained P-V and Q-δ coupling in his linearized load flow model which has been used for voltage security analysis. However, this model uses an iterative procedure, which is time consuming.

The use of distribution factors for analysis of the reactive power problem has been reported for the first time by M.Illic-Spong et al. [48]. They used S-E graph and its decoupled version Q-V graph to define the new distribution factors. Based on their work, Taylor et al. [102] presented an algorithm that can be used in analyzing reactive power contingencies. This approach utilized the widely used MW distribution factors in conjunction with another set of MVAR distribution factors to solve iteratively for the post-contingency bus voltage magnitude changes. Thus these algorithms also utilize an iterative scheme and do not really provide a set of distribution factors which can be used for direct calculation of post-outage states.

Lee and Chen [113] have presented a method to calculate distribution factors, defined in terms of only pre-outage reactive power flows, for transmission line and transformer outage studies. The distribution factors were computed utilizing the fast decoupled load flow equations. Review of various contingency selection methods are reported in references [55,58,112,152].

Schlueter et al. [122] suggested a multiple contingency selection method for transmission reliability and transfer capability studies. The use of pattern recognition techniques has been reported in reference [93, 161] for contingency screening. The application of expert systems in contingency selection has been reported in references [61,62].

The *security control* is an *energy management system* (EMS) [12, 27, 103] function which optimally schedules the system controls, constrained by the network power flows and system operating limits. By definition, this scheduling function falls into the generic category of optimal power flow (OPF). The objective function used in OPF can be minimization of one or a combination of the following :

(i) total cost of thermal generation;

(ii) total system real power transmission loss;

(iii) the sum of the reactive power injections;

(iv) the deviation of the voltages from preselected values;

(v) the emission of the thermal units;

(vi) the radiation of electromagnetic field;

(vii) the control actions.

The minimization of total cost of thermal generation is known as *economic dispatch* or *real power dispatch.* The objectives from (ii) to (iv) correspond to *optimal reactive power dispatch* and objective (v) corresponds to minimum *emission dispatch.* In some of the countries power engineers are also worrying about radiation level of electromagnetic field (objective-vi).

A lot of literature exists on both economic and optimal reactive power dispatch. A comprehensive survey of OPF methods was first published by Happ [16]. Subsequently IEEE working group [22,23] presented a bibliographical survey of the works on economic loading and security till 1979. Thereafter, Carpentier [42] presented a comprehensive survey and classified the OPF algorithms based on their solution methodology along with the developments till 1985. Chowdhary et al. [97] made a detailed review of recent advances in economic dispatch while the Huneaults et al. [73] and Joshi et al. [137] made a survey of OPF literature. The literatures pertaining to security and reactive power and voltage control are available in an IEEE bibliography [54]. In view of the availability of large number of review papers on OPF and security optimization, only a representative survey of some of important works in the area of security constrained OPF is being provided.

A number of methods have been proposed for security constrained rescheduling since 1960 . Some of them considered only MW security [4,51,78,104,123]. The reactive power security constraints in OPF have been reported in references [34,37,65,77,91,100,101,110]. This security constrained dispatch is usually implemented by adding additional constraints, known as *security constraints*, to the original dispatch problem. These constraints impose additional limits on branch flows and bus voltages for the post-disturbance configurations. In other words, the security constrained dispatch leads to the implementation of preventive control action in the system, and thus may result into a higher level of system security. However, the total number of contingency constraints imposed on security constrained optimal power flow (SCOPF) may be enormous.

Monticelli et al. [51] suggested a security constrained optimal power flow with post-contingency corrective scheduling. Their solution algorithm is based on mathematical programming decomposition techniques that allow the iterative solution of a base-case

economic dispatch and a separate contingency analysis with generation rescheduling to eliminate constraint violations. The Benders cut is used for decomposition.

Terra et al. [101] have presented a new method to solve the preventive security-constrained reactive power (Var) dispatch problem. A decomposition-coordination scheme is conceived in order to take advantage of tearing the network, the problem itself is decomposed into smaller subproblems. Techniques are presented for contingency simulation and for handling of these contingencies in the optimization process. The procedure has been given for the step-by-step solution and for on-line implementation.

Contaxis et al. [35] have proposed a methodology for solving the optimal load flow problem. The problem is formulated as a non-linear constrained optimization problem recognizing system losses, operating limits on the generating units and line security limits. The optimization problem has been solved by iterative scheme. At each iteration the optimal load flow problem is decomposed into a real subproblem and a reactive subproblem. The two subproblems are transformed into a quadratic programming problem by utilizing Z matrix and the generalized generation distribution factors. For reactive subproblem, the voltages of generators are determined by minimizing the loading of the slack generator or equivalently by minimizing the operating cost of the slack generator.

Ajjarapu et al. [77] have demonstrated a systematic methodology to allocate reactive power output of devices in a power system. This was achieved through the application of an active set analysis based on linear programming technique. Linearized sensitivity relationships of the power system have been used to obtain an objective function for minimizing the cost of installation. Taking outages in order of severity, the reactive power was allocated to rectify jointly all the outage constraints with minimum adjustment to control variables.

Most of the works available in the area of security constrained dispatch suffer from the problems associated with decomposition, linearization (discretization) and few others which are reported in literature [63, 74, 159]. The following conventional optimization methods have been used for the solution of OPF problems:

- Classical coordination method
- Linear programming method
- Quadratic programming method

- Newton's method
- Sequential linear programming or quadratic programming method
- Generalized reduced gradient method
- Interior point method
- Continuation method etc.

All these optimization techniques have their own merits and demerits. A comparative survey of these methods have been presented in references [14,137].

Artificial intelligence (AI) technology, particularly expert systems, neural networks and fuzzy systems have also been applied [47,116,127,131,134,150] to the optimization problems. Genetic Algorithms are optimization methods based on the mechanics of natural selection and genetics [69]. GAs have already been applied to some power system problems [106,119,133,136,138,146,149,153]. A text book [69] gives following features of GA;

> "GA is a blind search using stochastic operations, not deterministic rules. No information or knowledge concerning to objects are required. Operators are simple itself involving nothing more complex than random number generation (mutation), string copying (reproduction) and partial string exchanging (crossover)."

Bakirtzis et al. [149] have presented two GA solutions to the economic dispatch problem. Both of them outperform the dynamic programming based solution. Kenji Iba [146] has suggested a new approach to optimal reactive power planning based on genetic algorithm. The GA based method utilized unique intentional operators. The first being the *interbreeding* which is a kind of crossover using decomposed subsystems. This idea is similar to agricultural plant-breeding, since it assembles a whole system using good parts with various features. The second is the *gene-recombination* or *manipulation* which uses AI-based stochastic *If-then* rules.

Increased loading in most of the power systems, sometimes, lead their operation into a region where operating limits of one or more variables are violated and can not be brought within limit exercising the available controls. In this situation, optimal power dispatch may not remain feasible.

Very few works are available in literature for handling infeasibility of OPF or divergent power flow cases. To ensure feasible operation of the system under severe contingency cases, Monticelli et al. [51] have suggested the load curtailment and Burchett el al. [34] have proposed to use phantom generators at the selected buses in the network which normally remain idle. If a case is infeasible during optimization, the phantom generators are called upon to inject reactive power at a bus having the largest need. However, no criteria to select the critical buses for phantom generators has been suggested.

Granville et al. [143] have used an auxiliary optimization problem of minimizing the fictitious reactive power injections placed at all the buses which helps the user to determine the candidate buses for reactive source installation. They called this preliminary step as Feasibility analysis. The method described in this work decomposes the original problem into an investment and operation subproblems. The two methods have been described for operation in base case and contingency configuration. The first one is based on sensitivity coefficients and the other is based on Benders decomposition.

Overbye [151, 162] has introduced an algorithm to quantify the unsolvability of power flow problems where power flow equations have no real solutions and to determine the controls to return to solvability which is derived from a measure presented in reference [125]. The algorithm uses the minimum Euclidean distance in parameter space to quantify the unsolvability of the case. The sensitivities of the measure to system controls have been used to determine the best control action to restore the case to solvability.

1.3 Motivation

From the literature survey it appears that most of the works on voltage contingency selection have been attempted by using either of the following methods

- local solution method,
- one iteration of AC load flow method,
- linearized models and
- distribution factors method.

Amongst them the linearized load flow models and the distribution factor methods are more promising as they are non-iterative in nature and thus can provide faster solutions.

However, existing models of these methods, in general, provide results with large errors and many of them are based on decoupling and some unrealistic assumptions.

In order to assess the relative severity of the contingencies, scalar performance indices have been used. Two typical problems with the performance indices are the *masking* and *misranking* effects. The lack of discrimination in which the performance index for a case with many small violations can be comparable in value to the index for a case with one huge violation, is known as *masking effect.* By most of the operational standards, the latter case is much more severe. *Misranking* of contingencies are mainly due to the inaccuracies in the model used for computing the performance indices or monitored quantities. Misranking is characterized by errors in the computed order of relative severities of various contingencies. Masking effect to some extent, can be avoided by using higher order performance indices. However, to avoid the misranking, proper selection of weights for performance indices is required. One attempt to use optimal weights in the performance indices is by Halpin et al. [39] who have utilized a probability based model.

After performing the security assessment, if the system is found to be in *insecure state,* security controls are exercised in order to bring the system into *secure state.* It can be achieved by corrective rescheduling or by running security constrained optimal power flow, provided the available controls in the system are capable of overcoming the system insecurity. Most of the works on optimal power flow use the minimization of fuel cost of the fossil units and/or system transmission loss as objective. However, cost characteristics of generating units may not be available with certain utilities. This is specially true for some developing countries such as India. Hence, optimal power flow can not be formulated on the basis of cost criteria. Such utilities also need some guidelines to optimally adjust the real and reactive power outputs of sources. One possible criteria to allocate the optimal settings of both the real and reactive power outputs of sources, is to use minimization of the system transmission loss as an objective to both real and reactive power subproblems of OPF. This will, in addition, help in enhancing the load delivery capacity of those utilities which are facing shortage of power.

For solving optimal power flow, the conventional methods suggested in literature include the classical coordination method, linear programming, quadratic and Newton's methods etc. However, these methods, in general, require close initial guess of variables and suffer from the convergence difficulties and local optima. Genetic algorithm (GA) [69] is becoming popular due to its robustness in finding near optimal solution. GA works on

coding of parameters instead of their actual values and uses multiple path search along with probabilistic transition rules in parameter space. It has been applied to some of the power system problems and is yet to be tried for the solution of complete optimal power flow problem.

Conventional security constrained optimal power flow considers the contingency constraints to the optimal power flow problem which leads to the implementation of preventive control action. Though this formulation ensures a higher level of system security, it reduces the economic benefit of optimal operation. In order to maximize the economic benefit of optimal power flow, system operation in *correctively secure state* has been suggested [55]. Base case optimal power flow results are not modified for the contingency constraints. The corrective actions for each of the contingencies are planned, in advance, with the help of optimal power flows. However, sometimes, it may not be feasible to bring the system to normal state with available controls, specially following the severe contingencies. This leads to infeasibility of the optimal power flows. Very few works have been reported to handle infeasibility of optimal power flow or divergent power flow cases [34, 143, 151]. A corrective action planning to solve infeasibility of optimal power flow has been attempted in reference [34] by adding fictitious reactive power sources at problematic buses. However, detection of problematic buses has not been addressed.

Therefore, the motivations behind the work carried out in this thesis are:

(i) To develop more accurate models of linearized load flow suitable for predicting the bus voltages non-iteratively. The predicted bus voltages can be utilized for voltage contingency analysis.

(ii) To explore new set of distribution factors to directly compute post-outage voltages and reactive power output of the sources following the outage of a transmission branch or a generator.

(iii) To explore new higher order voltage and reactive power performance indices in order to eliminate the masking effects and a new method for selection of optimal weights of the performance indices in order to eliminate the misranking problem.

(iv) To develop a new optimal power flow model, considering minimization of system real power transmission loss as an objective, to determine the optimal settings of both

the real and reactive power outputs of the sources and apply the genetic algorithm for its solution.

(v) To suggest a method based on eigenvalue analysis for planning the location and size of the corrective controls in order to enhance the system voltage/reactive power security and to eliminate the infeasibility of optimal power flow problem.

1.4 Thesis Organization

The present Chapter 1 introduces the power system security and optimal power flow problems, presents a brief state-of-art survey on the subject, specially on some aspects of voltage security analysis and controls, and sets the motivation behind the research work carried out in this thesis.

In Chapter 2, six different models of new linearized load flows for voltage security analysis have been developed based on the principle of linearizing non-linear power flow equations (in both polar and rectangular coordinates) around complete operating range. Five models have been developed using the integral square error minimization and one model based on the least square error minimization principles.

Chapter 3 presents the developments of new set of distribution factors which have been computed using the sensitivity property of Newton-Raphson load flow Jacobian at a base operating point. Eight sets of distribution factors have been suggested which can be used to calculate the post-outage voltages and reactive power output of the sources following the outage of a transmission branch or a generator.

Chapter 4 investigates use of higher order voltage and reactive power performance indices to remove masking effect. In order to avoid the misranking effect, a new procedure to compute the optimal weights of the performance indices has been suggested.

Chapter 5 formulates the optimal power flow problem with a single objective of system transmission loss minimization in order to obtain optimal scheduling of both real and reactive power outputs of sources. The genetic algorithm has been used to solve the loss minimization problem and the results have been compared with those obtained by Flechter's quadratic programming technique.

Chapter 6 presents the development of a method for corrective action planning which has been used to determine the controls to enhance the voltage/reactive power security

and eliminating the infeasibility of the optimal power flow problem. The left eigenvector corresponding to the minimum eigenvalue of reduced power flow Jacobian has been utilized to compute the corrective controls.

All the models suggested in Chapter 2 to 6 have been tested on IEEE 14-bus, IEEE 30-bus and a practical 75-bus U.P. State Electricity Board systems.

Chapter 7 highlights the main findings and significant contributions of the thesis and identifies scope for future research in this area.

Chapter 2

New Linearized Load Flow Models for Voltage Contingency Analysis

2.1 Introduction

Voltage security monitoring and analysis have assumed importance in the present day stressed operation of power system networks. In order to minimize the computational time required for the security analysis, contingency selection is performed. This requires the use of extremely fast and approximate (as compared to the exact AC load flow) models for predicting the voltage profile for each outage case. Amongst various models suggested in past, linearized load flow methods have been popularly used.

Most of the existing works on linearized load flow use either iterative schemes [9,105] which require large CPU time or non-iterative schemes [31,130]. The existing models of non-iterative schemes have been derived using certain unrealistic assumptions such as the lines are assumed to be purely inductive and power injection at the buses are assumed to be constant [31,130]. In addition, they have utilized the P-V and Q-δ decoupling assumptions which may not be valid, specially, in heavily stressed power system conditions [154]. In general, these methods have been found to provide quite inaccurate results.

Hence, there exists a need to develop more accurate and fast methods for contingency analysis. In this Chapter, non-iterative linearized AC load flow models have been proposed based on the principles of *least square error* (LSE) and *integral square error* (ISE) minimization.

Six different versions of linearized load flow models in polar as well as in rectangular

coordinates have been developed and tested on IEEE 14-bus system, IEEE 30-bus system and on a 75-bus Indian system for the base case and contingency cases. The accuracies of these new linearized load flow models have also been compared with the solution obtained from one iteration of the Newton-Rhapson load flow (NRLF) method.

2.2 New Linearized Load Flow Models

The power flow equations at a bus-j of an N-bus system in polar coordinates are given as

$$P_j = \sum_{i=1}^{N} V_i V_j (G_{ij} \cos \delta_{ij} - B_{ij} \sin \delta_{ij}) \tag{2.1}$$

$$Q_j = \sum_{i=1}^{N} V_i V_j (-G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \tag{2.2}$$

and in rectangular coordinates as follows

$$P_j = \sum_{i=1}^{N} [G_{ij}(e_i e_j + f_i f_j) + B_{ij}(e_i f_j - e_j f_i)] \tag{2.3}$$

$$Q_j = \sum_{i=1}^{N} [G_{ij}(e_i f_j - e_j f_i) - B_{ij}(e_i f_i + f_i f_j)] \tag{2.4}$$

These algebraic power flow equations ((2.1) to (2.4)) are non-linear in nature. Several full AC load flow models [3, 5, 8, 11, 13, 21, 25, 108] have been developed to solve these power flow equations based on numerical solution techniques and some of them [11, 108] exploit certain specific properties of power system network such as P-V and Q-δ decoupling. For approximate solution of the load flow equations required in the security analysis, linear iterative models have also been suggested [9, 105]. In this Chapter, the non-iterative linearized load flow models have been developed using both *least square error* (LSE) and *integral square error* (ISE) minimization principles as described below.

A non-linear function f of variables x, y and z can be expressed in linearized form as $f \cong Ax + By + Cz + D$, where A, B, C and D are the constant coefficients. The error in the linearization can be defined as

$$\epsilon = f(x, y, z) - Ax - By - Cz - D \tag{2.5}$$

This error function ϵ can be minimized by using either an ISE or LSE minimization principle, resulting in two different models of linearized load flow which have been called linearized model-A and model-B, respectively.

2.2.1 Linearized Model-A

This model minimizes the integral of the squared error, written as

$$\epsilon = \int_{x_1}^{x_2} \int_{y_1}^{y_2} \int_{z_1}^{z_2} (f(x,y,z) - Ax - By - Cz - D)^2 dz dy dx \tag{2 6}$$

At minima of ϵ, the partial derivatives $\partial\epsilon/\partial A$, $\partial\epsilon/\partial B$, $\partial\epsilon/\partial C$ and $\partial\epsilon/\partial D$ will be zero. This results into four linear equations whose solution provides the values of unknowns A, B, C and D. Once the A, B, C and D coefficients are known, the non-linear function $f(x,y,z)$ can be replaced by the linearized relationship.

Depending on the approximations in the linearization of the non-linear load flow equations, it is possible to derive various models. Five different versions of the linearized load flows based on ISE minimization have been explored and are presented below. Three of them (versions A_1, A_2 and A_3) are in polar coordinates and two are in rectangular coordinates (versions A_4 and A_5).

2.2.1.1 Linearized Version A_1

In this version, the trigonometric functions in load flow equations (2.1) and (2.2) are linearized as

$$\cos\delta_{ij} \cong A\delta_{ij} + B \tag{2.7}$$

$$\sin\delta_{ij} \cong C\delta_{ij} + D \tag{2.8}$$

In equations (2.7) and (2.8), the coefficients A, B, C and D can be obtained by minimizing ISEs, as defined below

$$\epsilon_1 = \int_{\delta_{ij}^1}^{\delta_{ij}^2} [\cos\delta_{ij} - A\delta_{ij} - B]^2 d\delta_{ij} \tag{2.9}$$

$$\epsilon_2 = \int_{\delta_{ij}^1}^{\delta_{ij}^2} [\sin\delta_{ij} - C\delta_{ij} - D]^2 d\delta_{ij} \tag{2.10}$$

where δ_{ij}^1 and δ_{ij}^2 are the minimum and maximum operating values of the relative angle δ_{ij}. The values of A, B, C and D were obtained by minimizing the errors ϵ_1 and ϵ_2 in the range of δ_{ij}^1 to δ_{ij}^2 as given below.

(i) for δ_{ij} varying between 0^o to 10^o , we get

A = 0.0870934 B = 1.0025311

C = 0.9954362 D = 0.0001770

(ii) for δ_{ij} varying between 0^o to 20^o , we get

A = 0.1731205 B = 1.0100307

C = 0.9818125 D = 0.0014092

If voltages are assumed close to unity, one can express

$$V = 1 + \Delta V \tag{2.11}$$

The load flow equations (2.1) and (2.2) can be written in following form using the linearizations given in equations (2.9),(2.10) and (2.11).

$$P_j = \sum_{i=1}^{N} [(1 + \Delta V_i)(1 + \Delta V_j)\{G_{ij}(A\delta_{ij} + B) - B_{ij}(C\delta_{ij} + D)\}] \tag{2.12}$$

$$Q_j = \sum_{i=1}^{N} [(1 + \Delta V_i)(1 + \Delta V_j)\{-G_{ij}(C\delta_{ij} + D) - B_{ij}(A\delta_{ij} + B)\}] \tag{2.13}$$

Simplifying the above equations after ignoring $\Delta V_i \Delta V_j$, $\delta_{ij}\Delta V$, $\delta_{ij}\Delta V_i \Delta V_j$ terms, we get the following equations for the linearized version A_1.

$$P_j = \sum_{i=1}^{N} [K_{ij}\delta_{ij} + L_{ij}(\Delta V_i + \Delta V_j) + L_{ij}] \tag{2.14}$$

$$Q_j = \sum_{i=1}^{N} [M_{ij}\delta_{ij} + N_{ij}(\Delta V_i + \Delta V_j) + N_{ij}] \tag{2.15}$$

where

$$K_{ij} = AG_{ij} - CB_{ij}$$
$$L_{ij} = BG_{ij} - DB_{ij}$$
$$M_{ij} = -CG_{ij} - AB_{ij}$$
$$N_{ij} = -DG_{ij} - BB_{ij}$$

The equations (2.14) and (2.15) form the set of linearized equations of the following form

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = [A_L] \begin{bmatrix} \delta \\ \Delta V \end{bmatrix} \tag{2.16}$$

If N_q is the total number of P-V buses in an N-bus power system and bus-1 is slack bus, the equation (2.16) can be expressed in expanded form as

$$\begin{bmatrix} P_2' \\ P_3' \\ \vdots \\ P_N' \\ Q_{N_q+1}' \\ \vdots \\ Q_N' \end{bmatrix} = \begin{bmatrix} J^1 & J^2 \\ J^3 & J^4 \end{bmatrix} \begin{bmatrix} \Delta\delta_2 \\ \Delta\delta_3 \\ \vdots \\ \Delta\delta_N \\ \Delta V_{N_q+1} \\ \vdots \\ \Delta V_N \end{bmatrix} \tag{2.17}$$

The elements of matrices J^1, J^2, J^3 and J^4 will be as follows:

$J_{ii}^1 = K_{ii} - \sum_{j=1}^N K_{ij} \qquad i = 2, 3, \ldots N$

$J_{ij}^1 = K_{ij} \qquad i = 2, \ldots, N$ and $j = 2, \ldots, N (\neq i)$

$J_{ii}^2 = L_{ii} + \sum_{j=N_q+1}^N L_{ij} \qquad i = N_q + 1, \ldots, N$

$J_{ij}^2 = L_{ij} \qquad i = 2, \ldots, N$ and $j = N_q + 1, \ldots, N (\neq i)$

$J_{ii}^3 = M_{ii} - \sum_{j=1}^N M_{ij} \qquad i = N_q + 1, \ldots, N$

$J_{ij}^3 = M_{ij} \qquad i = N_q + 1, \ldots, N$ and $j = 2, \ldots, N (\neq i)$

$J_{ii}^4 = N_{ii} + \sum_{j=1}^N N_{ij} \qquad i = N_q + 1, \ldots, N$

$J_{ij}^4 = N_{ij} \qquad i = N_q + 1, \ldots, N$ and $j = N_q + 1, \ldots, N (\neq i)$

and

$$P_i' = P_i - \sum_{j=1}^N L_{ij} \qquad i = 2, \ldots, N \tag{2.18}$$

$$Q_i' = Q_i - \sum_{j=1}^N N_{ij} \qquad i = N_q + 1, \ldots, N \tag{2.19}$$

The solution of equation (2.17) directly provides the change in voltage magnitude and angle values. This requires one inversion of matrix $[A_L]$.

2.2.1.2 Linearized Version A_2

In this version, the terms $V_iV_j\cos\delta_{ij}$ and $V_iV_j\sin\delta_{ij}$ of equations (2.1) and (2.2) are linearized as

$$V_iV_j\cos\delta_{ij} \cong A_3V_i + B_3V_j + C_3\delta_{ij} + D_3 \tag{2.20}$$

$$V_iV_j\sin\delta_{ij} \cong A_4V_i + B_4V_j + C_4\delta_{ij} + D_4 \tag{2.21}$$

The coefficients $A_3, B_3, C_3, D_3, A_4, B_4, C_4$ and D_4 are calculated by minimizing integral square errors ϵ_3 and ϵ_4 over the voltage V in the range V^1 to V^2 and angles δ_{ij} in the range δ_{ij}^1 to δ_{ij}^2.

$$\epsilon_3 = \int_{\delta_{ij}^1}^{\delta_{ij}^2}\int_{V_j^1}^{V_j^2}\int_{V_i^1}^{V_i^2}(V_iV_j\cos\delta_{ij} - A_3V_i - B_3V_j - C_3\delta_{ij} - D_3)^2 dV_i dV_j d\delta_{ij} \tag{2.22}$$

$$\epsilon_4 = \int_{\delta_{ij}^1}^{\delta_{ij}^2}\int_{V_j^1}^{V_j^2}\int_{V_i^1}^{V_i^2}(V_iV_j\sin\delta_{ij} - A_4V_i - B_4V_j - C_4\delta_{ij} - D_4)^2 dV_i dV_j d\delta_{ij} \tag{2.23}$$

After computing the coefficients, a set of linear equations for P_j and Q_j in terms of variables V_i, V_j and δ_{ij} are obtained as follows.

$$P_j = \sum_{i=1}^{N}[R_{ij}\delta_{ij} + S_{ij}(V_i + V_j) + T_{ij}] \tag{2.24}$$

$$Q_j = \sum_{i=1}^{N}[U_{ij}\delta_{ij} + V_{ij}(V_i + V_j) + W_{ij}] \tag{2.25}$$

where

$$\begin{aligned}
R_{ij} &= C_3G_{ij} - C_4B_{ij}\\
S_{ij} &= A_3G_{ij} - A_4B_{ij} = B_3G_{ij} - B_4B_{ij}\\
T_{ij} &= D_3G_{ij} - D_4B_{ij}\\
U_{ij} &= -C_3B_{ij} - C_4G_{ij}\\
V_{ij} &= -A_3B_{ij} - A_4G_{ij} = -B_3B_{ij} - B_4G_{ij}\\
W_{ij} &= -D_3B_{ij} - D_4G_{ij}
\end{aligned}$$

The equations (2.24) and (2.25) form the model of linearized version A_2 and can be written in compact form as

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = [A_M]\begin{bmatrix} \delta \\ V \end{bmatrix} \tag{2.26}$$

The elements of matrix $[A_M]$ can be defined on the similar lines as for matrix $[A_L]$ in section 2.2.1.1. Its dimension is same as that of $[A_L]$.

2.2.1.3 Linearized Version A$_3$

In version A$_1$, the product terms $\Delta V_i \Delta V_j$, $\delta_{ij}\Delta V$, $\delta_{ij}\Delta V_i \Delta V_j$ have been ignored, assuming that they are small. However, to improve the accuracy of the equations (2.12) and (2.13), these terms can be retained in linearized form as

$$\delta_{ij}\Delta V_i \cong \alpha_1 \delta_{ij} + \beta_1 \Delta V_i + \gamma_1 \tag{2.27}$$

$$\delta_{ij}\Delta V_i \Delta V_j \cong \alpha_2 \delta_{ij} + \beta_2(\Delta V_i + \Delta V_j) + \gamma_2 \tag{2.28}$$

$$\Delta V_i \Delta V_j \cong \beta_3(\Delta V_i + \Delta V_j) + \gamma_3 \tag{2.29}$$

Using equations (2.27) to (2.29), the equations (2.12) and (2.13) can be rewritten as

$$P_j = \sum_{i=1}^{N}[R_{ij}\delta_{ij} + S_{ij}(\Delta V_i + \Delta V_j) + T_{ij}] \tag{2.30}$$

$$Q_j = \sum_{i=1}^{N}[U_{ij}\delta_{ij} + V_{ij}(\Delta V_i + \Delta V_j) + W_{ij}] \tag{2.31}$$

where

$$\begin{aligned}
R_{ij} &= (1 + 2\alpha_1 + \alpha_2)(AG_{ij} - CB_{ij}) \\
S_{ij} &= (\beta_1 + \beta_2)(AG_{ij} - CB_{ij}) + (1 + \beta_3)(BG_{ij} - DB_{ij}) \\
T_{ij} &= (2\gamma_1 + \gamma_2)(AG_{ij} - CB_{ij}) + (1 + \gamma_3)(BG_{ij} - DB_{ij}) \\
U_{ij} &= (1 + 2\alpha_1 + \alpha_2)(-CG_{ij} - AB_{ij}) \\
V_{ij} &= (\beta_1 + \beta_2)(-CG_{ij} - AB_{ij}) + (1 + \beta_3)(-DG_{ij} - BB_{ij}) \\
W_{ij} &= (2\gamma_1 + \gamma_2)(-CG_{ij} - AB_{ij}) + (1 + \gamma_3)(-DG_{ij} - BB_{ij})
\end{aligned}$$

The equations (2.30) and (2.31), forming model of linearized version A$_3$, can be written in compact form as

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = [A_N] \begin{bmatrix} \delta \\ \Delta V \end{bmatrix} \tag{2.32}$$

The elements of matrix $[A_N]$ is calculated in similar way as those of $[A_L]$ described in section 2.2.1.1 using the values of $R_{ij}, S_{ij}, T_{ij}, U_{ij}, V_{ij}$ and W_{ij} in place of K_{ij}, L_{ij}, M_{ij} and N_{ij}. The solution of above equation (2.32) gives the new voltage and angle values.

2.2.1.4 Linearized Version A$_4$

This version deals with the linearization of power flow equations (P_j and Q_j) in rectangular coordinates (equations (2.3) and (2.4)). The product of e (real part of voltage) and f (imaginary part of voltage) can easily be linearized as

$$e_i e_j \cong A_5 e_i + B_5 e_j + C_5 \tag{2.33}$$

$$f_i f_j \cong A_6 f_i + B_6 f_j + C_6 \tag{2.34}$$

$$e_i f_j \cong A_7 e_i + B_7 f_j + C_7 \tag{2.35}$$

The coefficients of e and f in equations (2.33) to (2.35) can be calculated using integral square error minimization. If one assumes the voltage magnitudes to vary from 0.90 to 1.10 pu and angles from -20° to 0°, then one can assume the variation of e to be between 0.846 to 1.10 and f to be between -0.376 to 0. The equations (2.33) to (2.35) can be expressed in following form describing the of linearized version A$_4$.

$$P_j = \sum_{i=1}^{N} [K_{ij} e_i + L_{ij} e_j + M_{ij} f_i + N_{ij} f_j + O_{ij}] \tag{2.36}$$

$$P_j = \sum_{i=1}^{N} [R_{ij} e_i + S_{ij} e_j + T_{ij} f_i + U_{ij} f_j + V_{ij}] \tag{2.37}$$

where

$$
\begin{aligned}
K_{ij} &= A_5 G_{ij} + A_7 B_{ij} \\
L_{ij} &= B_5 G_{ij} - A_7 B_{ij} \\
M_{ij} &= A_6 G_{ij} - B_7 B_{ij} \\
N_{ij} &= B_6 G_{ij} + B_7 B_{ij} \\
O_{ij} &= (C_5 + C_6) G_{ij} \\
R_{ij} &= A_7 G_{ij} - A_5 B_{ij} \\
S_{ij} &= -A_7 G_{ij} - B_5 B_{ij} \\
T_{ij} &= -B_7 G_{ij} - A_6 B_{ij} \\
U_{ij} &= B_7 G_{ij} - B_6 B_{ij} \\
V_{ij} &= -(C_5 + C_6) B_{ij}
\end{aligned}
$$

The equations (2.36) and (2.37) can be written in compact form as follows

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = [A_O'] \begin{bmatrix} e \\ f \end{bmatrix} \tag{2.38}$$

$[A_O']$, having dimension ($2N$-N_q-1) x ($2N$-2), is not a square matrix. However, it can be made square by adding the following relationship for P-V buses.

$$V_k^2 = e_k^2 + f_k^2 \qquad k = 2, \ldots, N_q \tag{2.39}$$

where V_k is specified voltage magnitude of k^{th} P-V bus. This equation (2.39) can also be linearized using ISE method as

$$e_k^2 \cong D_5 e_k + E_5 \tag{2.40}$$

$$f_k^2 \cong D_6 f_k + E_6 \tag{2.41}$$

Using equations (2.40) and (2.41), the equation (2.39) can be expressed as follows

$$V_k^2 - (E_5 + E_6) = |V_k^2|' = D_5 e_k + D_6 f_k \tag{2.42}$$

The equation (2.38) can be modified as

$$\begin{bmatrix} P' \\ Q' \\ |V_k^2|' \end{bmatrix} = [A_O] \begin{bmatrix} e \\ f \end{bmatrix} \tag{2.43}$$

The above matrix $[A_O]$ is a square matrix of dimension (2N-2) x (2N-2). A single matrix inversion of $[A_O]$ gives the solution of voltages.

2.2.1.5 Linearized Version $\mathbf{A_5}$

The real part of voltage (e) is normally close to unity and hence, one can express it as

$$e = 1 + \Delta e \tag{2.44}$$

Using equation (2.44), the equations (2.3) and (2.4) can be rewritten as

$$P_j = \sum_{i=1}^{N}[G_{ij}(1 + \Delta e_i + \Delta e_j + \Delta e_i \Delta e_j + f_i f_j) + B_{ij}(f_j + \Delta e_i f_j - \Delta e_j f_i - f_i)] \tag{2.45}$$

$$Q_j = \sum_{i=1}^{N}[G_{ij}(f_j + \Delta e_i f_j - \Delta e_j f_i - f_i) - B_{ij}(1 + \Delta e_i + \Delta e_j + \Delta e_i \Delta e_j + f_i f_j)] \tag{2.46}$$

The product terms $\Delta e_i \Delta e_j$, $f_i f_j$ and $\Delta e_i f_j$ or $\Delta e_j f_i$ has been linearized using ISE method and expressed as

$$\Delta e_i \Delta e_j \cong A_8 \Delta e_i + B_8 \Delta e_j + C_8 \tag{2.47}$$

$$f_i f_j \cong A_9 f_i + B_9 f_j + C_9 \tag{2.48}$$

$$\Delta e_i f_j \cong A_{10} \Delta e_i + B_{10} f_j + C_{10} \tag{2.49}$$

The equations (2.45) and (2.46) can be further simplified using equations (2.47) to (2.49) and written as

$$P_j = \sum_{i=1}^{N} [K_{ij} \Delta e_i + L_{ij} \Delta e_j + M_{ij} f_i + N_{ij} f_j + O_{ij}] \tag{2.50}$$

$$Q_j = \sum_{i=1}^{N} [R_{ij} \Delta e_i + S_{ij} \Delta e_j + T_{ij} f_i + U_{ij} f_j + V_{ij}] \tag{2.51}$$

where

$$\begin{aligned}
K_{ij} &= (1 + A_8) G_{ij} + A_{10} B_{ij} \\
L_{ij} &= (1 + B_8) G_{ij} - A_{10} B_{ij} \\
M_{ij} &= A_9 G_{ij} - (1 + B_{10}) B_{ij} \\
N_{ij} &= B_9 G_{ij} + (1 + B_{10}) B_{ij} \\
O_{ij} &= (1 + C_8 + C_9) G_{ij} \\
R_{ij} &= -(1 + A_8) B_{ij} + A_{10} G_{ij} \\
S_{ij} &= -(1 + B_8) B_{ij} - A_{10} G_{ij} \\
T_{ij} &= -A_9 B_{ij} - (1 + B_{10}) G_{ij} \\
U_{ij} &= -B_9 B_{ij} + (1 + B_{10}) G_{ij} \\
V_{ij} &= -(1 + C_8 + C_9) B_{ij}
\end{aligned}$$

The equation (2.39) can be written as follows

$$V_k^2 = (1 + 2\Delta e_k + \Delta e_k^2) + f_k^2 \quad k = 2, \ldots, N_q \tag{2.52}$$

The terms Δe_k^2 and f_k^2 in the above equation can be linearized as

$$\Delta e_k^2 \cong D_7 \Delta e_k + E_7 \tag{2.53}$$

$$f_k^2 \cong D_8 f_k + E_8 \tag{2.54}$$

Equation (2.52) can be written as

$$|V_k^2|' = V_k^2 - (1 + E_7 + E_8) = (2 + D_7)\Delta e_k + D_8 f_k \tag{2.55}$$

Equations (2.50), (2.51) and (2.55) form the model of version A_5 and can be written in following compact form

$$\begin{bmatrix} P' \\ Q' \\ |V_k^2|' \end{bmatrix} = [A_P] \begin{bmatrix} \Delta e \\ f \end{bmatrix} \tag{2.56}$$

The matrix $[A_P]$ is a square matrix of dimension (2N-2) x (2N-2) and one inversion of this matrix is required to determine the values of Δe and f.

2.2.2 Linearized Model-B

This model is based on minimization of the squared error (ϵ^2). The bus power S_i (either P_i or Q_i) at bus-i can be expressed as

$$S_i = \mathbf{f}(\mathbf{V}, \delta) \tag{2.57}$$

In linearized form, it can be written as

$$S_i \cong K_i + \sum_{j=1}^{N} F_{ij}\delta_j + \sum_{j=1}^{N} M_{ij}V_j \tag{2.58}$$

with K_i, F_{ij} and M_{ij} being the coefficients. If there were no errors in this approximation, one could have obtained unknowns K_i, F_{ij}, M_{ij} by directly equating equation (2.58) at known operating points. However, this approximation is bound to have some error due to the non-linear nature of the function.

The least square error method can be used to compute these coefficients requiring a more number of equations than the number of unknowns. For every power equation (P or Q) the unknowns are 2N+1. To compute the required coefficients, $m(m > 2N + 1)$ linear equations are required to be generated, which can be written as

$$\begin{bmatrix} S_i^1 \\ S_i^2 \\ \vdots \\ S_i^m \end{bmatrix} = \begin{bmatrix} 1 & \delta_1^1 & \dots & \delta_N^1 & V_1^1 & \dots & V_N^1 \\ 1 & \delta_1^2 & \dots & \delta_N^1 & V_1^2 & \dots & V_N^2 \\ \vdots & \vdots & & \vdots & \vdots & & \vdots \\ 1 & \delta_1^m & \dots & \delta_N^m & V_1^m & \dots & V_N^m \end{bmatrix} \begin{bmatrix} K_i \\ F_{i1} \\ \vdots \\ F_{iN} \\ M_{i1} \\ \vdots \\ M_{iN} \end{bmatrix} \tag{2.59}$$

or in compact form, it can be expressed as

$$\mathbf{b} = \mathbf{A}\mathbf{r} \tag{2.60}$$

where $\mathbf{b}$ is the bus power vector and vector $\mathbf{r}$ contains coefficients K_i, F_{ij} and M_{ij} (variables to be determined in equation (2.59)) and $\mathbf{A}$ is the coefficient matrix of equation (2.59) containing unity, voltage angle and magnitude terms.

The above m equations for each bus power expression can be generated by considering different operating conditions, where $[\delta_1^i, \dots, \delta_N^i, V_1^i, \dots, V_N^i]$ in equation (2.59) represent the bus voltage angles and magnitudes for the i^{th} operating condition.

The error vector can be defined as

$$\epsilon = \mathbf{A}\mathbf{r} - \mathbf{b} \tag{2.61}$$

Minimizing the norm of this error $(\mathbf{Ar} - \mathbf{b})$, equivalent to minimizing $\|\mathbf{Ar} - \mathbf{b}\|$, means minimizing the sum of the squared errors,

$$\epsilon_1^2 + \epsilon_2^2 + \dots + \epsilon_m^2 \tag{2.62}$$

where ϵ_i^2 is the square of the distance or error (ϵ_i). The least square solution [85] for the vector $\mathbf{r}$ is given by

$$\mathbf{r} = \left[\mathbf{A}^\mathbf{T}\mathbf{A}\right]^{-1}\mathbf{A}^\mathbf{T}\mathbf{b} \tag{2.63}$$

Once the constants are determined, it is necessary to compute the bus voltage magnitudes and angles for the given injections as

$$[S - K] = [B] \begin{bmatrix} \delta \\ V \end{bmatrix} \tag{2.64}$$

or

$$\begin{bmatrix} \delta \\ V \end{bmatrix} = [B]^{-1}[S-K] \tag{2.65}$$

The matrix $[B]$ in equation (2.64) is the constant coefficient matrix defined as

$$[B] = \begin{bmatrix} F_{11} & \dots & F_{1N} & M_{11} & \dots & M_{1N} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ F_{2N,1} & \dots & F_{2N,N} & M_{2N,1} & \dots & M_{2N,N} \end{bmatrix} \tag{2.66}$$

2.3 Numerical Results and Discussions

To establish the effectiveness of the proposed models of linearized load flow, the studies were conducted on IEEE 14-bus, IEEE 30-bus and a practical 75-bus systems as described in Appendices-B, C and D respectively. The range of δ_{ij} for linearization has been taken to be 0^o to 10^o for the IEEE 14-bus and the 30-bus systems while it has been taken as -5^o to 37^o for the 75-bus UPSEB system. A different range of δ_{ij} for UPSEB system (-5^o to 37^o) was selected based on the results obtained for the base case studies. It was found that using the above range for linearization yields minimum error.

The voltage range for linearization in all the three systems was considered to be from 0.85 to 1.10 pu. The ranges of e and f for linearization has been considered in all the three systems accordingly and computed using equations

$$e^{min} = min\{V^{min}\cos\delta^{min}, V^{min}\cos\delta^{max}\} \tag{2.67}$$

$$e^{max} = V^{max} \tag{2.68}$$

$$f^{min} = V^{min}\sin\delta^{min} \tag{2.69}$$

$$f^{max} = V^{max}\sin\delta^{max} \tag{2.70}$$

All five versions of model-A have been tried out for the IEEE 14-bus and IEEE 30-bus systems, and 75-bus Indian system to obtain voltages at the load buses for both the base case and for different outages. The investigation have been carried out on HP-9000/850 computers for the base case as well as contingency cases in all the three systems. The root mean square (RMS) errors in pu and maximum percentage errors have been calculated

Table 2.1: Comparison of load flow results for base case

	Systems	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	1 Iter. NRLF
RMS	14-bus	0.0019	0.0022	0.0016	0.0060	0.0060	0.0050
Error	30-bus	0.0021	0.0022	0.0022	0.0091	0.0091	0.0070
V(p.u.)	75-bus	0.0142	0.0143	0.0138	0.0980	0.0980	0.063
Maximum	14-bus	0.43	0.52	0.34	1.15	1.15	0.69
Error	30-bus	0.52	0.62	0.53	1.5291	1.52	1.32
V(%)	75-bus	3.50	3.51	3.45	19.05	19.05	10.75
CPU	14-bus	0.12	0.13	0.12	0.13	0.14	0.12
Time	30-bus	0.31	0.48	0.31	0.48	0.49	0.4370
(secs.)	75-bus	1.90	1.92	1.92	2.46	2.50	1.89

with respect to the results obtained from the unadjusted (without Q -limits check) full AC load flow.

Table 2.1 gives a summary of errors in voltages and CPU time required by all the five versions of linearized model-A for IEEE 14-bus, IEEE 30-bus and 75-bus Indian systems for the base case. The CPU time excludes the time required for calculation of constants. The bus voltage magnitudes of IEEE 14-bus system has been given in Table 2.2 for the base case. The base case results of IEEE 30-bus and 75-bus UPSEB systems have been presented in Tables 2.3 and 2.4, respectively. The bus voltage magnitudes obtained by Ist iteration of NRLF (polar coordinate) have also been given in these tables for all the three systems for the sake of comparison.

The following observations can be made from the results presented in Table 2.1.

(i) Of the proposed five linearized versions, version A_3 predicts the bus voltages more accurately. However, the performance of versions A_1, A_2 and A_3 are comparable.

(ii) The proposed versions A_1, A_2 and A_3 outperform the results of first iteration of NRLF for all the three systems.

(iii) R.M.S. error in voltage is quite small for all the versions. The error in version A_4 and version A_5 for all the three systems is almost same and the errors produced by these versions are relatively much higher than versions A_1 to A_3.

(iv) CPU time taken by the proposed A_1, A_2 and A_3 versions are comparable with the

Table 2.2: 14-bus system– Bus voltage magnitudes at base case

Bus No	Full NRLF	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	Model B	1 Iter. NRLF
1	1.060	1.059	1.060	1.060	1.060	1.060	1.060	1.060
2	1.045	1.045	1.045	1.045	1.058	1.059	1.045	1.045
3	1.070	1.069	1.070	1.070	1.071	1.073	1.070	1.070
4	1.010	1.009	1.010	1.010	1.011	1.011	1.010	1.010
5	1.090	1.089	1.090	1.090	1.092	1.094	1.090	1.090
6	1.064	1.063	1.062	1.063	1.067	1.068	1.065	1.071
7	1.057	1.053	1.052	1.052	1.060	1.061	1.059	1.064
8	1.030	1.031	1.031	1.032	1.034	1.034	1.025	1.036
9	1.025	1.025	1.025	1.026	1.029	1.029	1.021	1.031
10	1.051	1.048	1.046	1.047	1.054	1.055	1.056	1.057
11	1.057	1.054	1.054	1.055	1.059	1.060	1.065	1.062
12	1.055	1.053	1.053	1.054	1.056	1.057	1.054	1.059
13	1.050	1.047	1.047	1.048	1.051	1.052	1.050	1.054
14	1.036	1.030	1.029	1.031	1.038	1.038	1.038	1.041

first iteration of NRLF methods. However, versions A_4 and A_5 take comparatively more CPU time.

In order to establish the potential of linearized load flow to solve the contingency cases, outages were considered in 14-bus, 30-bus and 75-bus systems. The contingencies considered include single line/transformer outage and single generator outage. However, results for outage of only line (1-2) of IEEE 14-bus as well as of IEEE 30-bus systems and line (41-42) outage of 75-bus UPSEB system have been presented in Tables 2.5, 2.6, 2.7, respectively. These lines were carrying maximum power in the base case. From Tables 2.5 to 2.7, it is observed that maximum voltage errors in the case of these severe contingency cases are the minimum with version A_3 which are 2.57%, 4.97% and 4.89% for IEEE 14-bus, IEEE 30-bus and 75-bus UPSEB systems, respectively.

The model- B was tested on only IEEE 14-bus system for the base case and contingency cases. For the LSE minimization, the number of equations must be higher than unknown quantities. The number of coefficients to be computed for this system were 506 (=22 x 23) with the assumption that voltage at P-V buses (5 in numbers) are fixed to their specified values. If bus-1 is the slack bus, equation (2.58) can be written as

Table 2.3: 30-bus system– Bus voltage magnitudes at base case

Bus No.	Full NRLF	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	1 Iter. NRLF
1	1.060	1.059	1.059	1.059	1.060	1.060	1.060
2	1.045	1.044	1.044	1.044	1.058	1.058	1.045
3	1.010	1.009	1.009	1.009	1.013	1.013	1.010
4	1.082	1.081	1.081	1.081	1.088	1.088	1.082
5	1.010	1.009	1.009	1.009	1.010	1.010	1.010
6	1.071	1.070	1.070	1.070	1.073	1.073	1.071
7	1.040	1.042	1.042	1.042	1.047	1.047	1.043
8	1.024	1.025	1.025	1.025	1.032	1.032	1.022
9	1.046	1.046	1.046	1.047	1.052	1.052	1.040
10	1.079	1.085	1.086	1.085	1.095	1.095	1.066
11	1.015	1.018	1.018	1.018	1.020	1.020	1.025
12	1.002	1.003	1.003	1.003	1.005	1.005	1.007
13	1.010	1.012	1.012	1.013	1.016	1.016	1.017
14	1.031	1.030	1.030	1.031	1.038	1.038	1.025
15	1.027	1.026	1.026	1.027	1.034	1.034	1.021
16	1.029	1.029	1.029	1.030	1.036	1.036	1.025
17	1.020	1.020	1.020	1.021	1.028	1.028	1.017
18	1.013	1.012	1.012	1.013	1.022	1.022	1.009
19	1.009	1.007	1.007	1.008	1.017	1.017	1.005
20	1.012	1.011	1.011	1.012	1.020	1.020	1.009
21	1.015	1.015	1.015	1.016	1.024	1.024	1.012
22	1.017	1.017	1.017	1.017	1.026	1.026	1.014
23	1.020	1.020	1.020	1.021	1.029	1.029	1.015
24	1.021	1.021	1.021	1.021	1.031	1.031	1.015
25	1.052	1.055	1.055	1.055	1.066	1.066	1.041
26	1.035	1.037	1.037	1.037	1.048	1.048	1.024
27	1.023	1.027	1.028	1.028	1.028	1.028	1.034
28	1.012	1.014	1.014	1.014	1.018	1.018	1.019
29	1.060	1.064	1.064	1.064	1.077	1.077	1.047
30	1.050	1.052	1.052	1.052	1.067	1.067	1.036

Table 2.4: 75-bus system– Bus voltage magnitudes at base case

Bus No.	Full NRLF	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	1 Iter. NRLF
1	1.030	1.029	1.029	1.029	1.030	1.030	1.030
2	1.050	1.049	1.049	1.049	1.066	1.064	1.050
3	1.030	1.029	1.029	1.029	1.033	1.032	1.030
4	1.050	1.049	1.049	1.049	1.102	1.099	1.050
5	1.050	1.049	1.049	1.049	1.078	1.076	1.050
6	1.050	1.049	1.049	1.049	1.071	1.069	1.050
7	1.050	1.049	1.049	1.049	1.088	1.086	1.050
8	1.050	1.049	1.049	1.049	1.092	1.089	1.050
9	1.050	1.049	1.049	1.049	1.090	1.087	1.050
10	1.020	1.019	1.019	1.019	1.027	1.027	1.020
11	1.020	1.019	1.019	1.019	1.021	1.021	1.020
12	1.050	1.049	1.049	1.049	1.145	1.140	1.050
13	1.050	1.049	1.049	1.049	1.139	1.135	1.050
14	1.030	1.029	1.029	1.029	1.089	1.086	1.030
15	1.010	1.009	1.009	1.009	1.012	1.012	1.010
16	1.024	1.035	1.035	1.035	1.056	1.055	1.059
17	1.025	1.041	1.041	1.041	1.058	1.057	1.061
18	1.013	1.014	1.014	1.015	1.059	1.058	1.056
19	1.000	1.022	1.022	1.023	1.059	1.059	1.069
20	.992	.995	.995	.996	1.039	1.039	1.043
21	1.012	1.005	1.006	1.006	1.173	1.168	1.100
22	1.023	1.047	1.047	1.047	1.168	1.163	1.132
23	1.014	1.049	1.049	1.049	1.106	1.105	1.112
24	1.004	1.013	1.013	1.013	1.084	1.082	1.076
25	1.011	1.012	1.012	1.013	1.175	1.170	1.109
26	.994	1.027	1.027	1.028	1.085	1.083	1.089
27	.993	1.000	1.000	1.001	1.083	1.081	1.075
28	1.018	1.006	1.006	1.007	1.136	1.132	1.069
29	1.027	1.056	1.056	1.056	1.166	1.162	1.133
30	1.015	1.011	1.011	1.012	1.171	1.166	1.102
31	1.039	1.032	1.032	1.032	1.121	1.118	1.077
32	1.038	1.030	1.030	1.031	1.123	1.119	1.077
33	1.040	1.038	1.038	1.038	1.145	1.141	1.095
34	1.016	1.004	1.004	1.005	1.091	1.088	1.040
35	1.029	1.044	1.043	1.043	1.064	1.063	1.062
36	.999	1.015	1.015	1.016	1.050	1.050	1.061
37	.979	.983	.983	.984	1.029	1.029	1.040

Contd. ...

Table 2.4 (Contd.) ...

Bus No.	Full NRLF	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	1 Iter. NRLF
38	1.037	1.057	1.058	1.057	1.178	1.173	1.139
39	1.030	1.027	1.027	1.028	1.157	1.152	1.100
40	.996	.993	.993	.994	1.022	1.022	1.022
41	1.040	1.052	1.052	1.052	1.125	1.122	1.074
42	1.040	1.046	1.046	1.046	1.119	1.116	1.072
43	1.021	1.013	1.013	1.013	1.138	1.133	1.071
44	1.018	1.014	1.014	1.014	1.073	1.071	1.061
45	1.034	1.027	1.027	1.027	1.116	1.113	1.101
46	.982	.983	.983	.984	1.019	1.019	1.028
47	1.005	1.008	1.008	1.008	1.066	1.065	1.063
48	.979	.969	.969	.970	1.008	1.009	1.006
49	.968	.956	.956	.958	1.000	1.000	.996
50	.990	.993	.993	.995	1.042	1.041	1.048
51	.981	.966	.966	.968	1.119	1.116	1.082
52	.981	.947	.947	.949	1.148	1.144	1.087
53	1.012	.998	.998	.999	1.174	1.168	1.094
54	1.003	.990	.990	.991	1.112	1.109	1.063
55	.981	.955	.955	.957	1.086	1.083	1.039
56	1.015	1.004	1.004	1.005	1.148	1.144	1.077
57	1.001	.981	.981	.982	1.171	1.165	1.079
58	1.002	.981	.981	.982	1.163	1.158	1.072
59	1.003	.981	.982	.983	1.171	1.165	1.080
60	.996	.982	.982	.983	1.187	1.181	1.097
61	1.013	.996	.996	.997	1.169	1.164	1.089
62	1.023	1.007	1.007	1.008	1.142	1.138	1.077
63	.988	.965	.965	.966	1.099	1.096	1.048
64	.974	.965	.965	.966	1.029	1.028	1.028
65	1.012	1.004	1.005	1.005	1.173	1.168	1.099
66	.981	.979	.979	.980	1.030	1.030	1.033
67	1.003	1.010	1.010	1.010	1.081	1.079	1.074
68	1.003	1.005	1.005	1.005	1.060	1.059	1.055
69	.953	.951	.951	.953	1.006	1.007	1.016
70	.995	.978	.978	.979	1.191	1.185	1.097
71	.992	.994	.995	.995	1.076	1.075	1.067
72	.997	.982	.982	.984	1.188	1.182	1.099
73	1.033	1.023	1.023	1.023	1.127	1.125	1.110
74	1.015	1.050	1.050	1.049	1.107	1.105	1.113
75	1.029	1.065	1.065	1.064	1.163	1.159	1.136

Table 2.5: 14-bus system– Bus voltage magnitudes for line (1-2) outage

Bus No	Full NRLF	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	Model B	1 Iter. NRLF
1	1.060	1.059	1.059	1.060	1.060	1.060	1.060	1.060
2	1.045	1.044	1.044	1.045	1.079	1.079	1.045	1.045
3	1.070	1.069	1.069	1.070	1.109	1.109	1.070	1.070
4	1.010	1.009	1.009	1.010	1.069	1.069	1.010	1.010
5	1.090	1.089	1.089	1.090	1.136	1.136	1.090	1.090
6	1.058	1.063	1.063	1.063	1.112	1.112	1.117	1.072
7	1.050	1.053	1.053	1.052	1.111	1.111	1.130	1.063
8	1.010	1.036	1.036	1.031	1.053	1.053	1.030	1.041
9	1.013	1.028	1.028	1.025	1.062	1.062	1.027	1.034
10	1.045	1.047	1.047	1.046	1.104	1.104	1.151	1.057
11	1.053	1.054	1.054	1.054	1.104	1.104	1.172	1.062
12	1.055	1.053	1.053	1.053	1.100	1.100	1.029	1.059
13	1.049	1.047	1.047	1.047	1.096	1.096	1.056	1.054
14	1.031	1.030	1.030	1.029	1.092	1.092	1.095	1.041

$$P_i \cong K_i' + \sum_{j=2}^{N} F_{ij}\delta_j + \sum_{j=N_q+1}^{N} M_{ij}V_j \quad i = 2,\ldots,N \tag{2.71}$$

$$Q_i \cong K_i'' + \sum_{j=2}^{N} F_{ij}'\delta_j + \sum_{j=N_q+1}^{N} M_{ij}'V_j \quad i = N_q+1,\ldots,N \tag{2.72}$$

To compute 506 unknown coefficients, the load flow equations, for at least 23 operating points, are required. In this work, 50 operating points were generated to compute the coefficients.

For the base case study, the maximum voltage error with model-B, compared with full AC load flow results, was found to be 0.86% at bus-11 but in the case of line and generator outages, the errors were much larger as compared to other versions of model-A. The error is found to be as high as 11.34% for line (1-2) outage of the IEEE 14-bus system as presented in Table 2.5. Model-B was found to be quite inaccurate, specially for contingency cases. Hence, it was not tried for the other systems.

Table 2.6: 30-bus system– Bus voltage magnitudes for line (1-2) outage

Bus No.	Full NRLF	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	1 Iter. NRLF
1	1.060	1.059	1.059	1.059	1.060	1.060	1.060
2	1.045	1.044	1.044	1.044	1.097	1.097	1.045
3	1.010	1.009	1.009	1.009	1.057	1.057	1.010
4	1.082	1.081	1.081	1.081	1.181	1.181	1.082
5	1.010	1.009	1.009	1.009	1.099	1.099	1.010
6	1.071	1.070	1.070	1.070	1.140	1.140	1.071
7	1.033	1.032	1.032	1.033	1.123	1.123	1.043
8	1.015	1.006	1.006	1.006	1.113	1.113	1.022
9	1.037	1.036	1.036	1.036	1.122	1.122	1.042
10	1.069	1.056	1.057	1.056	1.171	1.171	1.066
11	.988	1.017	1.017	1.017	1.052	1.052	1.028
12	.996	1.001	1.001	1.001	1.074	1.074	1.009
13	1.000	1.010	1.010	1.011	1.064	1.064	1.019
14	1.022	1.015	1.015	1.016	1.116	1.116	1.028
15	1.017	1.009	1.009	1.010	1.113	1.113	1.023
16	1.020	1.014	1.014	1.015	1.113	1.113	1.026
17	1.010	1.001	1.001	1.002	1.110	1.110	1.017
18	1.004	.991	.991	.993	1.106	1.106	1.010
19	.999	.985	.985	.986	1.104	1.104	1.006
20	1.002	.989	.989	.990	1.106	1.106	1.009
21	1.005	.994	.994	.995	1.108	1.108	1.012
22	1.007	.996	.996	.997	1.110	1.110	1.014
23	1.011	1.000	1.000	1.001	1.112	1.112	1.016
24	1.011	.997	.997	.998	1.116	1.116	1.015
25	1.041	1.027	1.028	1.028	1.146	1.146	1.041
26	1.024	1.008	1.008	1.009	1.133	1.133	1.024
27	.983	1.032	1.032	1.032	1.042	1.042	1.042
28	1.004	1.009	1.010	1.010	1.069	1.069	1.020
29	1.050	1.030	1.030	1.030	1.161	1.161	1.047
30	1.039	1.013	1.014	1.014	1.156	1.156	1.036

Table 2.7: 75-bus system– Bus voltage magnitudes for line (41-42) outage

Bus No.	Full NRLF	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	1 Iter. NRLF
1	1.030	1.029	1.029	1.029	1.030	1.030	1.030
2	1.050	1.049	1.049	1.049	1.066	1.064	1.050
3	1.030	1.029	1.029	1.029	1.033	1.032	1.030
4	1.050	1.049	1.049	1.049	1.104	1.101	1.050
5	1.050	1.049	1.049	1.049	1.079	1.077	1.050
6	1.050	1.049	1.049	1.049	1.072	1.070	1.050
7	1.050	1.049	1.049	1.049	1.089	1.087	1.050
8	1.050	1.049	1.049	1.049	1.095	1.092	1.050
9	1.050	1.049	1.049	1.049	1.090	1.087	1.050
10	1.020	1.019	1.019	1.019	1.028	1.028	1.020
11	1.020	1.019	1.019	1.019	1.021	1.021	1.020
12	1.050	1.049	1.049	1.049	1.201	1.194	1.050
13	1.050	1.049	1.049	1.049	1.051	1.051	1.050
14	1.030	1.029	1.029	1.029	1.090	1.087	1.030
15	1.010	1.009	1.009	1.009	1.014	1.014	1.010
16	1.020	1.030	1.030	1.030	1.056	1.056	1.059
17	1.020	1.038	1.038	1.038	1.058	1.057	1.061
18	1.004	1.006	1.006	1.005	1.060	1.059	1.057
19	.988	1.013	1.013	1.013	1.060	1.059	1.070
20	.983	.986	.986	.985	1.039	1.038	1.044
21	1.001	.985	.985	.984	1.175	1.170	1.100
22	1.006	1.030	1.030	1.030	1.168	1.164	1.132
23	.992	1.035	1.036	1.036	1.108	1.106	1.112
24	.989	.999	.999	.998	1.084	1.083	1.076
25	.997	.992	.992	.991	1.176	1.171	1.109
26	.969	1.016	1.016	1.016	1.084	1.082	1.089
27	.975	.986	.986	.985	1.084	1.082	1.076
28	1.011	.992	.992	.992	1.138	1.134	1.070
29	1.012	1.040	1.040	1.040	1.168	1.164	1.133
30	1.004	.992	.992	.991	1.173	1.168	1.102
31	1.035	1.023	1.023	1.022	1.122	1.119	1.077
32	1.033	1.020	1.021	1.020	1.124	1.121	1.077
33	1.033	1.026	1.027	1.026	1.146	1.142	1.095
34	1.013	.996	.996	.995	1.094	1.091	1.040
35	1.024	1.040	1.040	1.040	1.064	1.063	1.062
36	.989	1.007	1.007	1.006	1.051	1.050	1.061
37	.970	.972	.972	.971	1.029	1.029	1.040

Contd. ...

Table 2.7 (Contd.) ...

Bus No.	Full NRLF	Version A_1	Version A_2	Version A_3	Version A_4	Version A_5	1 Iter. NRLF
38	1.023	1.041	1.041	1.041	1.179	1.174	1.139
39	1.022	1.012	1.012	1.012	1.158	1.154	1.100
40	.991	.987	.987	.987	1.021	1.021	1.022
41	1.025	1.060	1.060	1.061	1.174	1.168	1.077
42	1.042	1.014	1.014	1.013	1.071	1.069	1.064
43	1.014	1.000	1.000	1.000	1.140	1.135	1.071
44	1.012	1.003	1.003	1.003	1.076	1.074	1.061
45	1.024	1.010	1.010	1.009	1.120	1.118	1.101
46	.976	.974	.974	.973	1.019	1.019	1.028
47	.994	.996	.996	.995	1.066	1.065	1.063
48	.974	.962	.962	.961	1.008	1.008	1.006
49	.964	.949	.949	.948	.999	.999	.996
50	.980	.982	.982	.981	1.042	1.041	1.048
51	.962	.942	.942	.941	1.119	1.116	1.083
52	.962	.917	.917	.915	1.148	1.144	1.088
53	1.002	.977	.977	.976	1.176	1.170	1.094
54	.994	.974	.974	.973	1.115	1.111	1.063
55	.974	.936	.936	.935	1.091	1.088	1.039
56	1.007	.988	.988	.988	1.150	1.146	1.077
57	.991	.959	.959	.958	1.173	1.167	1.080
58	.993	.961	.961	.960	1.165	1.160	1.072
59	.993	.960	.960	.959	1.173	1.167	1.080
60	.982	.957	.957	.956	1.188	1.182	1.098
61	1.004	.976	.976	.975	1.171	1.165	1.089
62	1.016	.992	.992	.991	1.144	1.140	1.077
63	.980	.946	.946	.945	1.104	1.100	1.047
64	.965	.952	.952	.951	1.028	1.027	1.028
65	1.001	.984	.984	.983	1.175	1.170	1.099
66	.972	.968	.968	.967	1.030	1.029	1.033
67	.989	.996	.996	.995	1.081	1.080	1.073
68	.993	.995	.995	.994	1.060	1.059	1.056
69	.944	.938	.938	.936	1.006	1.007	1.017
70	.980	.952	.952	.951	1.192	1.186	1.098
71	.976	.980	.981	.980	1.077	1.075	1.068
72	.982	.958	.958	.956	1.189	1.183	1.099
73	1.021	1.003	1.003	1.003	1.132	1.129	1.110
74	.991	1.036	1.036	1.036	1.108	1.106	1.113
75	1.015	1.050	1.051	1.051	1.165	1.161	1.136

2.4 Conclusions

In the present Chapter, new linearized load flow techniques have been developed which compute voltage magnitudes at load buses with acceptable accuracy for both base case and contingency cases. The concept of minimization of least square error and integral square error have been explored, possibly for the first time, in linearizing the power flow equations over the possible operating range. From the results obtained on the three systems, the following conclusions can be made :

(i) Amongst the six proposed linearized versions, five based on ISE minimization (versions A_1 to A_5) and one based on LSE minimization (model-B), the version A_3 in polar coordinates, provides more accurate results as compared with the other versions. The versions A_1, A_2 and A_3 provide far superior results as compared to those obtained with the first iteration of NRLF (in polar coordinates). The model-B is found to be the least accurate.

(ii) The proposed linearized models are non-iterative in nature and takes approximately the same CPU time as the first iteration of NRLF method.

(iii) For some of the contingency cases, where AC load flow method diverges, the proposed methods are able to predict the approximate bus voltage magnitudes.

In view of the above, the proposed linearized load flow models, specially version A_3 of model-A, can be effectively used for voltage contingency analysis. From numerical simulation, it was found that the errors in the predicted value of voltage angles by proposed models are quite high. Hence, these models can not be used for post-outage power calculations.

Chapter 3

Voltage and Reactive Power Distribution Factors for Outage Analysis

3.1 Introduction

In Chapter 2, six linearized load flow models were developed for voltage contingency analysis. Amongst them some of the models, specially the model A_3, were found to provide quite accurate results in terms of predicting the post-outage bus voltages. However, these linearized models involve inversion of a matrix of almost the same size as the Jacobian for each outage case and hence, require additional CPU time. Moreover, these linearized load flow models do not handle the reactive power limit violation of the generators. Further the voltage angles predicted by the linearized load flow models are found to be inaccurate and hence, they can not be used to predict the change in reactive power output of the sources. The change in reactive power output of the sources may be required in contingency selection to form a suitable performance index for ranking the contingencies.

Distribution factors have been popularly used for the real power security analysis [38, 68]. Some of the attempts to derive the distribution factors for reactive power or voltage security include the efforts of Illic-Spong et al. [48] and Taylor et al. [102]. Their models are based on fast decoupled load flow (FDLF) [11] and require nine sets of distribution factors to calculate the reactive power flow of a transmission branch. The results presented in their work show that in most of the cases, the normalized errors in the load flow solution

using the distribution factors [48,102] are greater than 10% which are more than 30% in few cases.

Lee and Chen [113] have suggested voltage distribution factors for line outages derived from the FDLF equations. However, the P-V and Q-δ decoupling assumptions may not remain valid during system stressed conditions [154]. Hence, the use of FDLF based model is not appropriate for obtaining the distribution factors. Rao [118] and Singh et al. [138] have suggested the distribution factors for both voltage and reactive power calculations which were derived by exploiting the sensitivity property of Newton-Raphson load flow (NRLF) Jacobian available at the end of the base load flow solution. In the above two works, line outage voltage distribution factors were expressed in terms of only reactive power flow in the transmission units prior to the contingency. These factors do not reflect the effect of the real power flow which may also affect the bus voltages significantly, specially, under heavily loaded conditions.

Hence, in this Chapter, new sets of distribution factors have been suggested which can be used for direct computation of bus voltages as well as reactive power output of sources following a line/transformer or a generator outage. The voltage and reactive power distribution factors have been defined in terms of the pre-outage real and reactive power flows in the lines/outputs of generators. They have been derived using an efficient method exploiting the sensitivity properties of NRLF Jacobian available at the end of base load flow. The accuracy of the proposed distribution factors in predicting the bus voltages and reactive power output of sources have been established on IEEE 14-bus, IEEE 30-bus and a practical 75-bus UPSEB systems.

3.2 Power Flow Model of Transmission Branches

The transmission branches consist of transmission lines and transformers. The models used for these two elements in deriving the distribution factors are described below.

3.2.1 Transmission Line Model

Fig. 3.1 shows a transmission line-l represented by its lumped Π-equivalent parameters connected between bus-i and bus-j. The complex power flowing from bus-i to bus-j ($\bar{S}_{ij} = P_{ij} + jQ_{ij}$) can be expressed as

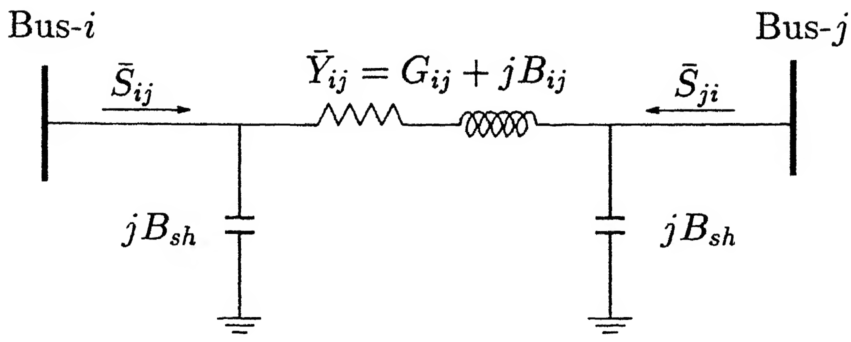

Figure 3.1: Π-equivalent model of a transmission line

$$\begin{aligned}
\bar{S}_{ij}^* &= P_{ij} - jQ_{ij} = \bar{V}_i^* \bar{I}_{ij} \\
&= \bar{V}_i^*[(\bar{V}_i - \bar{V}_j)\bar{Y}_{ij} + \bar{V}_i(jB_{sh})] \\
&= V_i^2[G_{ij} + j(B_{ij} + B_{sh})] - \bar{V}_i^* \bar{V}_j (G_{ij} + jB_{ij})
\end{aligned} \tag{3.1}$$

Equating the real and imaginary parts in the above equation, the expression for real and reactive power flows can be written as

$$P_{ij} = V_i^2 G_{ij} - V_i V_j G_{ij} \cos(\delta_i - \delta_j) - V_i V_j B_{ij} \sin(\delta_i - \delta_j) \tag{3.2}$$

$$Q_{ij} = -V_i^2(B_{ij} + B_{sh}) - V_i V_j G_{ij} \sin(\delta_i - \delta_j) + V_i V_j B_{ij} \cos(\delta_i - \delta_j) \tag{3.3}$$

Similarly, the real and reactive power flows from bus-j to bus-i can be expressed as

$$P_{ji} = V_j^2 G_{ij} - V_i V_j G_{ij} \cos(\delta_i - \delta_j) + V_i V_j B_{ij} \sin(\delta_i - \delta_j) \tag{3.4}$$

$$Q_{ji} = -V_j^2(B_{ij} + B_{sh}) + V_i V_j G_{ij} \sin(\delta_i - \delta_j) + V_i V_j B_{ij} \cos(\delta_i - \delta_j) \tag{3.5}$$

Outage of any of the branches causes redistribution of real and reactive power flows in the network and hence, changes the voltage profile. Since the real and reactive power flows at the sending and the receiving ends are different, neither of them can be used to define the outage distribution factors. Hence, the average or transmitted powers as defined below have been used for this purpose.

$$P_l^T = \frac{1}{2}(P_{ij} - P_{ji}) \tag{3.6}$$

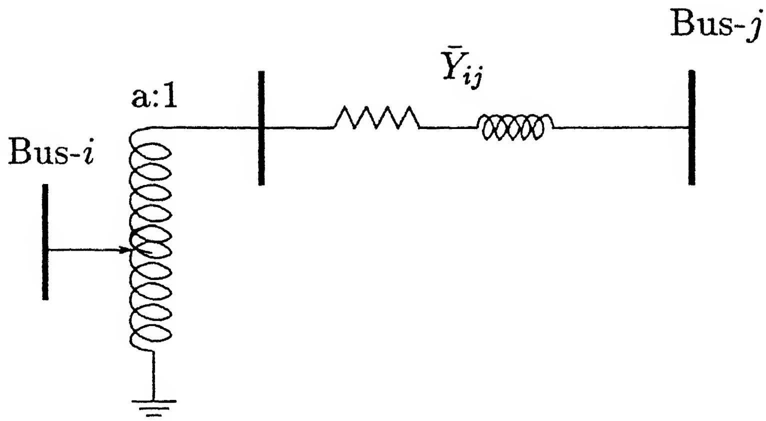

Figure 3.2: Transformer single-line diagram

$$Q_l^T = \frac{1}{2}(Q_{ij} - Q_{ji}) \tag{3.7}$$

From equations (3.2) to (3.7), P_l^T and Q_l^T can be expressed as

$$P_l^T = \frac{1}{2}(V_i^2 - V_j^2)G_{ij} - V_iV_jB_{ij}\sin(\delta_i - \delta_j) \tag{3.8}$$

$$Q_l^T = -\frac{1}{2}(V_i^2 - V_j^2)(B_{ij} + B_{sh}) - V_iV_jG_{ij}\sin(\delta_i - \delta_j) \tag{3.9}$$

3.2.2 Transformer Model

A transformer-l connected between bus-i and bus-j and having tapping ratio $a : 1$ is shown in Fig. 3.2. $\bar{Y}_{ij}$ is the series admittance of the transformer. The Π-equivalent model of the transformer is shown in Fig. 3.3. The real and reactive power flows from bus-i to bus-j can be derived similar to the transmission line model and can be expressed as

$$\begin{aligned} P_{ij} &= Re\{\bar{V}_i^*[(\bar{V}_i - \bar{V}_j)\tfrac{\bar{Y}_{ij}}{a} + \bar{V}_i\bar{Y}_{ij}\tfrac{1}{a}(\tfrac{1}{a} - 1)]\} \\ &= V_i^2\tfrac{G_{ij}}{a^2} - V_iV_j\tfrac{G_{ij}}{a}\cos(\delta_i - \delta_j) - V_iV_j\tfrac{B_{ij}}{a}\sin(\delta_i - \delta_j) \end{aligned} \tag{3.10}$$

and

$$\begin{aligned} Q_{ij} &= -Im\{V_i^2\tfrac{\bar{Y}_{ij}}{a^2} - \bar{V}_i^*\bar{V}_j\tfrac{\bar{Y}_{ij}}{a}\} \\ &= -V_i^2\tfrac{B_{ij}}{a^2} - V_iV_j\tfrac{G_{ij}}{a}\sin(\delta_i - \delta_j) + V_iV_j\tfrac{B_{ij}}{a}\cos(\delta_i - \delta_j) \end{aligned} \tag{3.11}$$

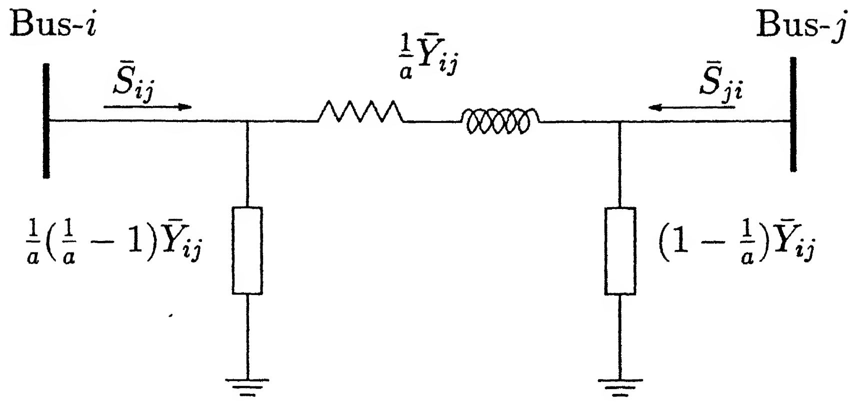

Figure 3.3: Π-equivalent model of transformer

Similarly, real and reactive power flows from bus-j to bus-i can be written as

$$\begin{aligned} P_{ji} &= Re\{\bar{V}_j^*[(\bar{V}_j - \bar{V}_i)\tfrac{\bar{Y}_{ij}}{a} + \bar{V}_i\bar{Y}_{ij}(1-\tfrac{1}{a})]\} \\ &= V_j^2 G_{ij} - V_i V_j \tfrac{G_{ij}}{a}\cos(\delta_i - \delta_j) + V_i V_j \tfrac{B_{ij}}{a}\sin(\delta_i - \delta_j) \end{aligned} \tag{3.12}$$

$$\begin{aligned} Q_{ji} &= -Im\{V_j^2\bar{Y}_{ij} - \bar{V}_j^*\bar{V}_i\tfrac{\bar{Y}_{ij}}{a}\} \\ &= -V_j^2 B_{ij} + V_i V_j \tfrac{G_{ij}}{a}\sin(\delta_i - \delta_j) + V_i V_j \tfrac{B_{ij}}{a}\cos(\delta_i - \delta_j) \end{aligned} \tag{3.13}$$

The average of real and reactive power flows through the transformer-l, as defined by equations (3.6) and (3.7), can be expressed as

$$P_l^T = \frac{1}{2}(\frac{V_i^2}{a^2} - V_j^2)G_{ij} - V_i V_j \frac{B_{ij}}{a}\sin(\delta_i - \delta_j) \tag{3.14}$$

$$Q_l^T = -\frac{1}{2}(\frac{V_i^2}{a^2} - V_j^2)B_{ij} - V_i V_j \frac{G_{ij}}{a}\sin(\delta_i - \delta_j) \tag{3.15}$$

3.3 Proposed Distribution Factors

In the voltage security or reactive power security studies, the effect of line/transformer or generator outages on the system voltage profile and reactive power output of sources are required to be computed. Two groups of distribution factors have been suggested viz. the *voltage distribution factors* which can be used to compute the post-outage voltage profile in the system and the *reactive power distribution factors* which can be used to compute

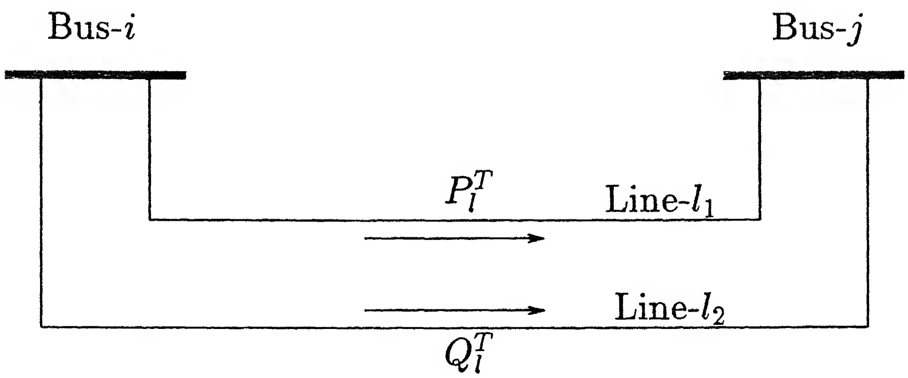

Figure 3.4: Schematic diagram of a line$-l$

the post-outage output of the reactive power sources. For a line/transformer outage, these factors have been termed as *line outage voltage distribution factors* (LOVDFs) and *line outage reactive power distribution factors* (LOQDFs), respectively. In the case of generator outage, they have been termed as the *generator outage voltage distribution factors* (GOVDFs) and the *generator outage reactive power distribution factors* (GOQDFs), respectively. These factors are defined as following:

3.3.1 Line Outage Distribution Factors

Consider the outage of a line or a transformer$-l$ carrying an average real power P_l^T and reactive power Q_l^T. The transmission unit can be represented by two fictitious lines l_1 and l_2 in parallel as shown in Fig. 3.4, one carrying only the real power P_l^T and the other carrying only the reactive power Q_l^T. Cumulative effect of outages of these fictitious lines l_1 and l_2, determined individually, will provide the total effect of outage of the transmission unit-l. If change in voltage at bus-i is ΔV_i^P due to outage of the line-l_1 carrying only real power P_l^T and ΔV_i^Q the change in the voltage following the outage of line-l_2 carrying only reactive power Q_l^T, the net change in voltage at bus-i will be the sum of ΔV_i^P and ΔV_i^Q for the line/transformer-l outage. The line outage voltage distribution factors $a_{l_i}^P$ and $a_{l_i}^Q$ corresponding to the outage of fictitious line-l_1 and line-l_2, respectively can be defined as

$$a_{l_i}^P = \frac{\Delta V_i^P}{P_l^T} \tag{3.16}$$

and

$$a_{li}^{Q} = \frac{\Delta V_i^Q}{Q_l^T} \qquad i = 1, \ldots, N \;\; \& \;\; l = 1, \ldots, N_l \tag{3.17}$$

Similarly, for the outage of the above line-l, the change in reactive power output of a source (say source-j) can be obtained as the sum of the changes due to outage of the fictitious lines l_1 and l_2. The line outage reactive power distribution factors denoted as c_{lj}^P and c_{lj}^Q corresponding to the outage of the two fictitious lines l_1 and l_2 respectively, as defined below, can be used for computation of the post-outage reactive power output of the sources.

$$c_{lj}^{P} = \frac{\Delta Q_{Gj}^P}{P_l^T} \tag{3.18}$$

and

$$c_{lj}^{Q} = \frac{\Delta Q_{Gj}^Q}{Q_l^T} \qquad j = 1, \ldots, N_q \;\; \& \;\; l = 1, \ldots, N_l \tag{3.19}$$

Where N, N_l and N_q are the total number of buses, lines and reactive power sources in the system. ΔQ_{Gj}^P and ΔQ_{Gj}^Q are the changes in reactive power output of source-j due to outage of the fictitious lines l_1 and l_2, respectively. If the pre-outage real or reactive power flows (P_l^T or Q_l^T) of the transmission unit is zero, corresponding distribution factor has been taken as zero.

3.3.2 Generator Outage Distribution Factors

Consider the outage of a generator-g having real power output P_{Gg} and reactive power output Q_{Gg} during pre-outage condition. The generator-g can be assumed to consist of two fictitious sources g_1 and g_2 representing purely real power source with output P_{Gg} and purely reactive power source having output Q_{Gg}, respectively. Cumulative effect of outage of these sources has been used to simulate outage of generator-g. Assume that the outages of these fictitious sources g_1 and g_2 change the voltage at bus-i by ΔV_i^P and ΔV_i^Q, respectively and the reactive power output of another source-j in the system by ΔQ_{Gj}^P and ΔQ_{Gj}^Q, respectively. The corresponding generator outage voltage distribution factors b_{gi}^P and b_{gi}^Q can be defined as

$$b_{gi}^{P} = \frac{\Delta V_i^P}{P_{Gg}} \tag{3.20}$$

and

$$b_{gi}^{Q} = \frac{\Delta V_i^{Q}}{Q_{Gg}} \qquad i = 1, \ldots, N \;\; \& \;\; g = 1, \ldots, N_q \tag{3.21}$$

Similarly, the generator outage reactive power distribution factors d_{gj}^{P} and d_{gj}^{Q} can be defined as

$$d_{gj}^{P} = \frac{\Delta Q_{Gj}^{P}}{P_{Gg}} \tag{3.22}$$

and

$$d_{gj}^{Q} = \frac{\Delta Q_{Gj}^{Q}}{Q_{Gg}} \qquad g = 1, \ldots, N \;\; \& \;\; j = 1, \ldots, N_q (\neq g) \tag{3.23}$$

While simulating a generator outage, it has been assumed that the real power outage will be met by the slack bus generator only.

The above eight sets of distribution factors (equation (3.16) to (3.23)) can be directly used to compute the post-contingency system voltage profile and reactive power output of the sources. If pre-outage voltage of the bus-i and reactive power output of a source-j are V_i^0 and Q_{Gj}^0, respectively, then the post-outage voltage V_i^n at a bus-i can be computed as

$$V_i^n = V_i^0 + a_{li}^{P} P_l^T + a_{li}^{Q} Q_l^T \qquad i = 1, \ldots, N \tag{3.24}$$

and the post-outage reactive power output of the source-j, Q_{Gj}^n can be computed as

$$Q_{Gj}^n = Q_{Gj}^0 + c_{lj}^{P} P_l^T + c_{lj}^{Q} Q_l^T \qquad j = 1, \ldots, N_q \tag{3.25}$$

for a line/transformer-l outage.

For a generator-g outage, these quantities can be computed as

$$V_i^n = V_i^0 + b_{gi}^{P} P_{Gg} + b_{li}^{Q} Q_{Gg} \qquad i = 1, \ldots, N \tag{3.26}$$

and

$$Q_{Gj}^n = Q_{Gj}^0 + d_{gj}^{P} P_{Gg} + d_{gj}^{Q} Q_{Gg} \qquad j = 1, \ldots, N_q (\neq g) \tag{3.27}$$

3.4 Calculation of Distribution Factors

For computation of voltage and reactive power distribution factors as defined in equations (3.16) to (3.23), the base case values of line flows and output of sources as well as the effect of each outage on bus voltages and reactive power output of sources are required to be known. A new approach utilizing the sensitivity properties of the Newton-Raphson base case load flow Jacobian has been suggested to compute the post-outage changes in bus voltage magnitudes and reactive power generations.

The NRLF equations in polar coordinates [19] relate power mismatch with voltage corrections as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} \tag{3.28}$$

When Q-limits of the sources are considered, the size of Jacobian $[J]$ will be ($2N$-N_q+m-1)x($2N$-N_q+m-1), where m is the number of P-V buses converted to P-Q type following the violation of generator Q-limits. Consider an extended Jacobian $[J^*]$ at the end of base case load flow of size ($2N$-2) x ($2N$-2) with all source buses (except slack bus) treated as P-Q type. This matrix $[J^*]$ can be formed at the end of load flow easily by augmenting $(\partial Q/\partial\delta)$ and $(\partial Q/\partial V.V)$ elements corresponding to all P-V buses (except slack bus) in the final Jacobian $[J]$. A sensitivity matrix $[S]$ can be defined as $[S] = [J^*]^{-1}$. This directly provides the sensitivity relationship between bus powers and voltages and can be used to compute new bus voltage angles and magnitudes using the following equation, if the changes in bus power injections are known.

$$\begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} = [S] \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{3.29}$$

If the generator or line outages are simulated, as changes in real and reactive power injections, the post-outage changes in voltage magnitudes and angles can be directly computed using equation (3.29). In order to simulate the effect of the real and reactive power changes separately, equation (3.29) can be rewritten as

$$\begin{bmatrix} \Delta\delta^P + \Delta\delta^Q \\ \frac{\Delta V^P}{V} + \frac{\Delta V^Q}{V} \end{bmatrix} = [S] \begin{bmatrix} \Delta P \\ 0 \end{bmatrix} + [S] \begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} \tag{3.30}$$

where superscript P denotes the change in voltage angle or magnitude due to change in real power injection and superscript Q due to the change in reactive power injection. The above equation (3.30) can be decomposed into two sets of equations as following

$$\begin{bmatrix} \Delta\delta^P \\ \frac{\Delta V^P}{V} \end{bmatrix} = [S] \begin{bmatrix} \Delta P \\ 0 \end{bmatrix} \tag{3.31}$$

$$\begin{bmatrix} \Delta\delta^Q \\ \frac{\Delta V^Q}{V} \end{bmatrix} = [S] \begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} \tag{3.32}$$

The total change in bus voltage magnitudes and angles will be summation of the changes computed from equations (3.31) and (3.32) separately. Thus, the change in voltages from pre-outage to the post-outage condition can be expressed as

$$\Delta V = \Delta V^P + \Delta V^Q \tag{3.33}$$

and

$$\Delta\delta = \Delta\delta^P + \Delta\delta^Q \tag{3.34}$$

With the new complex bus voltages known, the post-outage reactive power output of sources and hence, the changes in these outputs can be computed. The attractive feature of this approach is that it does not require any additional load flow simulation for the contingencies. Thus, the distribution factors can be updated and the post-outage quantities using them can be calculated very fast. The procedure for simulating line and generator outages in the sensitivity relationship and calculation of the distribution factors are given below.

3.4.1 Line Outage Voltage Distribution Factors

Fig. 3.5 shows the pre-outage state of a part of a power system network, where line-l connecting bus-i and bus-j, is to be considered for outage study. Fig. 3.6 shows the post-outage state of the power system in which line-l is out of service. Usual simulation of the line outage requires modification of $[Y_{bus}]$ to exclude the parameters of line-l which changes the Jacobian and hence, involves a time extensive process. In order to retain the original $[Y_{bus}]$ and also the elements of the Jacobian and the sensitivity matrix, line outage has been simulated by considering two fictitious generators at bus-i and bus-j and a fictitious line having same parameter as the original line. By retaining a fictitious line of same parameter, $[Y_{bus}]$ remains unaffected. The power flow in this fictitious line is considered as the pre-outage power flow in the actual line. The power injected due to the

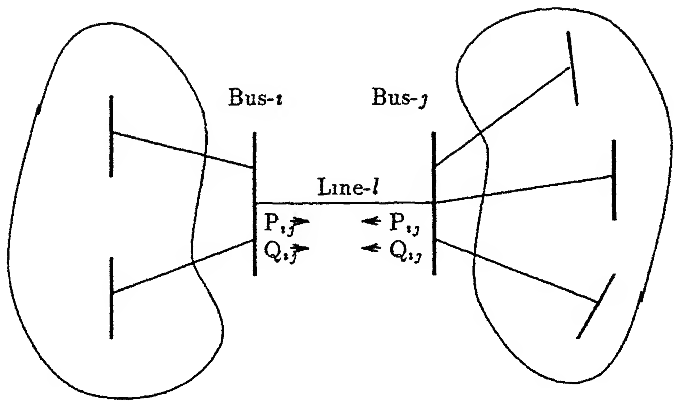

Figure 3.5: Pre-outage state of the power system

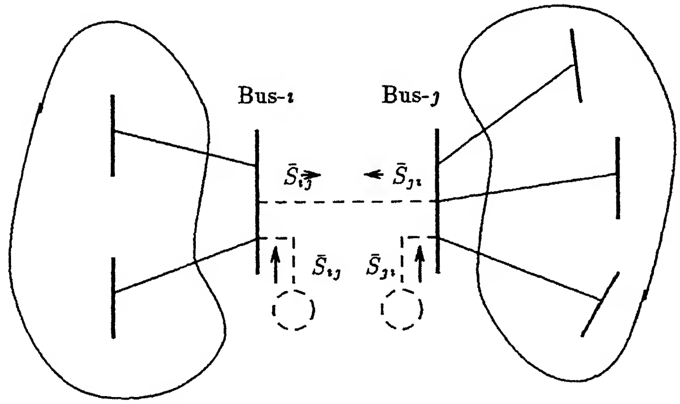

Figure 3.6: Post-outage state of the power system

two fictitious sources have been taken same as the line flows at the two ends in order to make the net power to be zero and thus, simulating the line outage condition. Hence, the changes in bus powers from pre-outage to post-outage state at bus-i and bus-j for outage of line-l are

$$\Delta P_i = P_{ij}, \qquad \Delta P_j = P_{ji} \tag{3.35}$$

and

$$\Delta Q_i = Q_{ij}, \qquad \Delta Q_j = Q_{ji} \tag{3.36}$$

For outage of the line-l, all the elements of power mismatch vectors in equations (3.31) and (3.32), will be zero except those corresponding to bus-i and bus-j as defined in equations (3.35) and (3.36). If either bus-i or bus-j is slack bus, only one non-zero element will appear in the $[\Delta P]$ and $[\Delta Q]$ vectors.

The solution of equations (3.31) and (3.32) provides the changes in bus voltage angles and magnitudes from pre-outage to post-outage condition corresponding to the outage of only real power and only reactive power flows of the line, respectively. With the changes in voltage magnitudes at all the buses known (slack bus voltage assumed to be constant), the line outage voltage distribution factors can be computed using equations (3.16) and (3.17). P_l^T and Q_l^T are computed from the base load flow results using equations (3.6) and (3.7). The factors a_{li}^P and a_{li}^Q can be calculated for each line outage, considering one at a time. Thus, the total number of line outage voltage distribution factors for outage of only real power or only reactive power flows of lines will be $(N\text{x}N_l)$ each. These can be stored in computer memory, say as matrices $[A^P]$ and $[A^Q]$, respectively, to carry out voltage contingency analysis.

3.4.2 Generator Outage Voltage Distribution Factors

Fig. 3.7 shows the pre-outage state of a generator-g which is connected to a bus-i. Fig. 3.8 shows the post-outage state of power system in which generator-g is taken out.

The changes in power injection at bus-i from pre-outage to post-outage can be given as

$$\Delta P_i = -P_g \tag{3.37}$$

$$\Delta Q_i = -Q_g \tag{3.38}$$

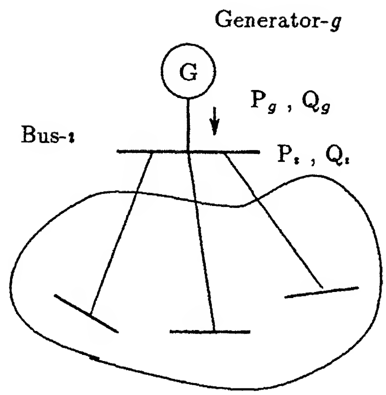

Figure 3.7: Pre-outage state of the power system

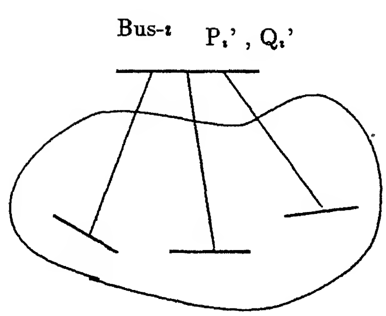

Figure 3.8: Pre-outage state of the power system

With these power mismatches, the equations (3.31) and (3.32) are solved separately to compute changes in bus voltage magnitudes ΔV^P and ΔV^Q, respectively. The generator outage voltage distribution factors (GOVDFs) are computed for outage of each generator, taken one at a time, using equations (3.20) and (3.21). These factors, thus obtained, are stored in the computer memory, say as matrices $[B^P]$ and $[B^Q]$, respectively, for the contingency analysis. Outage of slack bus generator have not been simulated in the present study. Its simulation will require considering another generator as slack bus and redefining matrices $[J]$ and $[S]$ accordingly.

3.4.3 Line Outage Reactive Power Distribution Factors

Consider the outage of a line-l. The change in bus voltage magnitudes and angles can be calculated on the similar lines as described in section 3.4.1. Using the new computed values of voltage magnitudes and angles, the reactive power output at the source buses and hence, the change in their reactive power outputs from pre-outage (Q^0_{Gg}) to post-outage condition can be computed. The change in reactive power output of the source-g due to only real power and only reactive power outage of the line can be written as

$$\Delta Q^P_{Gg} = Q^P_{Gg} - Q^0_{Gg} \tag{3.39}$$

$$\Delta Q^Q_{Gg} = Q^Q_{Gg} - Q^0_{Gg} \tag{3.40}$$

where the Q^P_{Gg} is calculated by using voltage magnitudes V^P ($=V^0 + \Delta V^P$) and angles δ^P ($= \delta^0 + \Delta\delta^P$) and the Q^Q_{Gg} by using voltage magnitudes V^Q ($=V^0 + \Delta V^Q$) and angles δ^Q ($= \delta^0 + \Delta\delta^Q$). The V^0 and δ^0 are the pre-outage bus voltage magnitudes and angles, respectively. The line outage reactive power distribution factors (LOQDFs) can be calculated using equations (3.18) and (3.19) for each line outage taken one at a time.

Thus the total number of line outage reactive power distribution factors for the real power outage or the reactive power outage are N_lxN_q which can be stored in the memory of computer, say as matrices $[C^P]$ and $[C^Q]$, respectively.

3.4.4 Generator Outage Reactive Power Distribution Factors

For outage of a generator, the change in bus voltage angles and magnitudes are computed by equations (3.31) and (3.32) exactly on similar lines as described in section 3.4.2. The

post-outage voltages are, thus, computed by adding these changes in voltages to their base case values. Using the post-outage bus voltage magnitudes and angles, the reactive powers (Q_{Gg}^{P} and Q_{Gg}^{Q}) and hence, the change in reactive power generations (ΔQ_{Gg}^{P} and ΔQ_{Gg}^{Q}) from the pre-outage to post-outage, can be computed using equations (3.39) and (3.40). The generator outage reactive power distribution factors (GOQDFs) can be calculated for outage of all the generators, taken one at a time, using equations (3.22) and (3.23). These factors are stored in the memory of the computer, as matrices $[D^{P}]$ and $[D^{Q}]$, respectively and can be used for the contingency analysis. Each of these matrices will contain (N_q-1 x N_q) elements.

3.5 Numerical Results and Discussions

To establish the effectiveness of the proposed distribution factors, outage studies were conducted on following three sample systems:

(i) IEEE 14-bus system as described in Appendix-B,

(ii) IEEE 30-bus system as described in Appendix-C and

(iii) A practical 75-bus UP State Electricity Board (UPSEB) system as described in Appendix-D.

The voltage magnitudes and reactive power output of the sources calculated by the new distribution factors are compared with the Newton-Raphson load flow results obtained for the post-outage conditions. Voltage error has been defined as

$$\epsilon^{V} = |V^{PF} - V^{DF}| \tag{3.41}$$

where V^{PF} are the post-outage bus voltages calculated by the power flow program and V^{DF} the post-outage bus voltages calculated by the distribution factors. For the present study, contingencies of all the lines, taken one at a time for all the three systems and outage of all the generators (except slack bus generator), taken one at a time, were simulated. The change in reactive power outputs of sources ΔQ_{Gg}^{P} and ΔQ_{Gg}^{Q} for outages of only real power and only reactive power flows of line/output of generators, from the base case, have been calculated on the assumption that the total change in reactive power ΔQ_{Gg} is the summation of ΔQ_{Gg}^{P} and ΔQ_{Gg}^{Q}.

Table 3.1: Line outage voltage distribution factors $[A^P]$

Line-	Bus-1	Bus-2	Bus-3	Bus-4	Bus-5	Bus-6	Bus-7
1	.0000	-.0053	-.0302	-.0092	-.0090	-.0092	-.0062
2	.0000	-.0038	-.0067	-.0067	-.0170	-.0175	-.0199
3	.0000	-.0058	-.0119	-.0102	-.0282	-.0289	-.0339
4	.0000	-.0198	-.0394	-.0282	-.0361	-.0370	-.0383
5	.0000	-.0003	-.0226	-.0092	-.0188	-.0193	-.0200
6	.0000	.0070	-.0025	.0396	-.0038	-.0039	-.0040
7	.0000	.0039	.0036	.0081	.0111	.0114	.0114
8	.0000	-.0191	-.0167	-.0187	-.0172	-.0176	-.0181
9	.0000	-.0115	-.0244	-.0572	-.0268	-.0275	-.0281
10	.0000	.0560	.1016	.0875	.1305	.1336	.1411
11	.0000	-.0042	-.0263	-.0173	-.0299	-.0306	-.0314
12	.0000	-.0020	-.0053	-.0035	-.0112	-.0115	-.0140
13	.0000	.0002	-.0045	.0006	.0027	.0027	.0034
14	.0000	-.0024	.0042	-.0048	-.0153	-.0157	-.0197
15	.0000	-.0018	-.0086	-.0031	-.0065	-.0066	-.0078
16	.0000	-.0024	-.0069	-.0043	-.0106	-.0108	-.0133
17	.0000	-.0013	-.0186	-.0016	.0004	.0004	.0009
18	.0000	.0017	-.0062	.0036	.0123	.0126	.0159
19	.0000	-.0006	.0018	-.0011	-.0040	-.0041	-.0054
20	.0000	-.0031	.0036	-.0062	-.0192	-.0197	-.0248

Contd. ...

Table 3.1 (Contd.) ...

Line-	Bus-8	Bus-9	Bus-10	Bus-11	Bus-12	Bus-13	Bus-14
1	-.0103	-.0121	-.0093	-.0182	-.0295	-.0260	-.0145
2	-.0083	-.0087	-.0184	-.0135	-.0074	-.0094	-.0159
3	-.0129	-.0133	-.0313	-.0231	-.0132	-.0164	-.0272
4	-.0376	-.0345	-.0387	-.0391	-.0399	-.0399	-.0396
5	-.0221	-.0177	-.0205	-.0215	-.0228	-.0226	-.0215
6	-.0021	-.0037	-.0038	-.0033	-.0027	-.0028	-.0036
7	.0010	.0117	.0103	.0073	.0042	.0050	.0089
8	-.0154	-.0167	-.0180	-.0175	-.0171	-.0173	-.0181
9	-.0216	-.0264	-.0277	-.0263	-.0250	-.0255	-.0275
10	.0957	.1118	.1368	.1218	.1051	.1108	.1309
11	-.0232	-.0294	-.0308	-.0288	-.0270	-.0276	-.0303
12	-.0045	-.0045	-.0129	-.0096	-.0058	-.0070	-.0113
13	-.0005	.0010	-.0237	-.0151	-.0042	-.0030	.0008
14	-.0026	-.0067	-.0304	-.0573	.0030	-.0003	-.0120
15	-.0035	-.0041	-.0082	-.0086	-.0958	-.0235	-.0147
16	-.0042	-.0057	-.0126	-.0102	-.0223	-.0548	-.0315
17	-.0046	-.0017	-.0016	-.0090	-.0254	-.0372	-.0892
18	.0013	.0051	.0255	-.0305	-.0052	-.0021	.0087
19	-.0006	-.0016	-.0043	-.0015	.0741	-.0313	-.0168
20	-.0037	-.0085	-.0212	-.0104	.0100	.0234	-.0786

Table 3.2: Line outage voltage distribution factors $[A^Q]$

Line-	Bus-1	Bus-2	Bus-3	Bus-4	Bus-5	Bus-6	Bus-7
1	.0000	.0947	.2647	.1558	.2207	.2260	.2409
2	.0000	-.0068	-.0640	-.0110	-.1520	-.1556	-.1207
3	.0000	.1150	.2802	.2089	.3114	.3189	.3419
4	.0000	-.0748	-.1812	-.1226	-.1662	-.1702	-.1780
5	.0000	.0390	-.0073	.0199	-.0009	-.0010	-.0023
6	.0000	-.0678	-.1553	-.1108	-.1695	-.1736	-.1755
7	.0000	.0047	.0023	.0155	.0183	.0187	.0159
8	.0000	-.0560	-.0483	-.0541	-.0493	-.0505	-.0517
9	.0000	.1339	.1265	.1695	.1304	.1335	.1364
10	.0000	.0010	.0032	.0017	-.1545	.0054	.0046
11	.0000	.0060	-.0522	-.0308	-.0598	-.0612	-.0613
12	.0000	.0027	-.0137	.0055	.0494	.0506	-.0344
13	.0000	.0001	-.0169	.0007	.0097	.0099	.0147
14	.0000	.0035	.0633	.0048	-.0092	-.0094	-.0178
15	.0000	.0023	.0225	.0037	.0041	.0041	.0038
16	.0000	.0021	.0281	.0032	-.0001	-.0001	-.0024
17	.0000	.0013	-.0317	.0033	.0252	.0258	.0373
18	.0000	.0349	.1237	.0622	.1641	.1680	.2148
19	.0000	.0003	.0093	.0004	-.0023	-.0024	-.0039
20	.0000	.0151	.1297	.0248	.0325	.0333	.0339

Contd. ...

Table 3.2 (Contd.) ...

Line-	Bus-8	Bus-9	Bus-10	Bus-11	Bus-12	Bus-13	Bus-14
1	.2227	.1983	.2470	.2567	.2665	.2660	.2564
2	-.0169	-.0138	-.1114	-.0884	-.0691	-.0735	-.1018
3	.2194	.2765	.3333	.3083	.2888	.2942	.3268
4	-.1774	-.1558	-.1799	-.1813	-.1834	-.1840	-.1839
5	-.0113	.0015	-.0032	-.0053	-.0071	-.0067	-.0043
6	-.1326	-.1703	-.1731	-.1649	-.1590	-.1610	-.1722
7	-.0093	.0239	.0136	.0080	.0034	.0043	.0110
8	-.0438	-.0482	-.0515	-.0501	-.0492	-.0497	-.0517
9	.1138	.1281	.1357	.1317	.1290	.1303	.1362
10	.0019	.0023	.0044	.0038	.0034	.0035	.0042
11	-.0425	-.0611	-.0601	-.0564	-.0536	-.0544	-.0593
12	.0036	.0076	-.0309	-.0225	-.0154	-.0169	-.0272
13	-.0009	.0012	-.0571	-.0373	-.0147	-.0125	.0028
14	.0103	.0057	-.0354	-.0740	.0581	.0526	.0132
15	.0056	.0047	.0072	.0147	-.1100	-.0235	-.0083
16	.0055	.0039	.0030	.0154	-.0175	-.0567	-.0267
17	.0002	.0049	.0253	-.0027	-.0466	-.0586	-.1501
18	.0699	.0817	.2724	.1440	.1323	.1393	.1850
19	.0012	.0005	-.0016	.0038	.1011	-.0301	-.0158
20	.0353	.0317	.0513	.0901	.1623	.1882	-.0164

Table 3.3: Generator outage voltage distribution factors $[B^P]$

Gen-	Bus-1	Bus-2	Bus-3	Bus-4	Bus-5	Bus-6	Bus-7
2	.0000	-.0194	-.0169	-.0190	-.0174	-.0178	-.0183
3	.0000	-.0254	-.0703	-.0379	-.0457	-.0468	-.0451
4	.0000	.0000	.0000	.0000	.0000	.0000	.0000
5	.0000	.0000	.0000	.0000	.0000	.0000	.0000

Table 3.3 (Contd.) ...

Gen-	Bus-8	Bus-9	Bus-10	Bus-11	Bus-12	Bus-13	Bus-14
2	-.0156	-.0169	-.0182	-.0177	-.0173	-.0175	-.0183
3	-.0485	-.0472	-.0486	-.0580	-.0701	-.0666	-.0549
4	.0000	.0000	.0000	.0000	.0000	.0000	.0000
5	.0000	.0000	.0000	.0000	.0000	.0000	.0000

Table 3.4: Generator outage voltage distribution factors $[B^Q]$

Gen-	Bus-1	Bus-2	Bus-3	Bus-4	Bus-5	Bus-6	Bus-7
2	.0000	-.0497	-.0429	-.0479	-.0437	-.0448	-.0458
3	.0000	-.0410	-.2557	-.0700	-.1370	-.1403	-.1668
4	.0000	-.0461	-.0706	-.1564	-.0755	-.0774	-.0785
5	.0000	-.0400	-.1315	-.0716	-.3737	-.2211	-.1912

Table 3.4 (Contd.) ...

Gen-	Bus-8	Bus-9	Bus-10	Bus-11	Bus-12	Bus-13	Bus-14
2	-.0388	-.0428	-.0456	-.0444	-.0437	-.0441	-.0459
3	-.0894	-.0906	-.1839	-.2200	-.2525	-.2472	-.2056
4	-.0615	-.0753	-.0777	-.0744	-.0721	-.0730	-.0775
5	-.0790	-.0942	-.1819	-.1577	-.1378	-.1426	-.1730

Table 3.5: Line outage reactive power distribution factors $[C^P]$

Line-	Gen-1	Gen-2	Gen-3	Gen-4	Gen-5
1	.1386	.0001	.0152	.0000	.0000
2	.1059	.0000	.0012	.0000	.0000
3	.1626	.0000	.0016	.0000	.0000
4	.3406	.0175	-.0001	.0015	-.0001
5	.1419	.0081	.0000	.0012	.0000
6	-.0990	-.0053	.0000	-.0109	.0000
7	-.0631	-.0013	-.0003	-.0003	.0000
8	.2139	.0232	.0001	-.0002	-.0001
9	.3065	.0295	.0002	.0252	-.0001
10	-.9959	.0000	.0000	.0000	.0000
11	.2041	.0130	.0003	.0033	-.0001
12	.0567	.0000	.0004	.0000	.0000
13	-.0005	.0000	.0000	.0000	.0000
14	.0511	.0000	.0064	.0000	.0000
15	.0460	.0000	.0049	.0000	.0000
16	.0585	.0000	.0084	.0000	.0000
17	.0429	.0000	.0007	.0000	.0000
18	-.0342	.0000	-.0007	.0000	.0000
19	.0118	.0000	.0006	.0000	.0000
20	.0679	.0000	.0011	.0000	.0000

Table 3.6: Line outage reactive power distribution factors $[C^Q]$

Line-	Gen-1	Gen-2	Gen-3	Gen-4	Gen-5
1	-2.6796	.0000	.2268	-.0001	-.0001
2	.1974	.0000	.0000	.0000	.0002
3	-3.0224	.0000	.0000	-.0001	.0000
4	2.1242	.0000	-.0001	.0002	.0001
5	-.6349	1.3133	.0000	.0000	.0000
6	1.7965	.0000	.0000	.1774	-.0001
7	-.0399	.0000	.0000	.0000	.0000
8	1.1851	-1.1401	-.0001	.0002	.0001
9	-2.8732	2.3653	.0000	.3609	.0000
10	-.0259	.0000	.0000	.0000	-1.0346
11	.0875	.9784	.0000	.0001	.0000
12	-.0638	.0000	.0000	.0000	.0000
13	.0010	.0000	.0000	.0000	.0000
14	-.1084	.0000	1.0590	.0000	.0000
15	-.0671	.0000	1.0380	.0000	.0000
16	-.0630	.0000	1.0406	.0000	.0000
17	-.0257	.0000	-.0001	.0000	.0000
18	-.9323	.0000	.0000	.0000	.0000
19	-.0118	.0000	.0000	.0000	.0000
20	-.4261	.0000	-.0001	.0000	.0000

Table 3.7: Generator outage reactive power distribution factors $[D^P]$

Gen-	Gen-1	Gen-2	Gen-3	Gen-4	Gen-5
2	.1922	.0000	.0000	.0000	.0000
3	.4708	.0058	.0000	.0006	-.0001
4	.0000	.0000	.0000	.0000	.0000
5	.0000	.0000	.0000	.0000	.0000

Table 3.8: Generator outage reactive power distribution factors $[D^Q]$

Gen-	Gen-1	Gen-2	Gen-3	Gen-4	Gen-5
2	1.0504	.0000	.0001	-.0003	-.0001
3	1.1274	.0000	.0000	-.0005	-.0005
4	1.0921	.0002	.0001	.0000	-.0002
5	1.0630	.0000	.0000	-.0005	.0000

The post-outage voltage magnitudes at all the buses for the above four contingency cases are given in Table 3.9, calculated from the load flow as well as by using the distribution factors. The corresponding errors ϵ^V are also presented in this table for the above mentioned outages. Table 3.10 shows the post-outage reactive power output of the sources calculated from the load flow (Q^{PF}) and the distribution factors (Q^{DF}). From Table 3.9, it can be seen that the largest voltage error is 0.016 pu in the case of line (2-4) outage, while it is only 0.025 pu and 0.008 pu in the case of line (5-6) and transformer (9-6) outages, respectively. For generator-2 outage, the maximum voltage error is 0.026 pu. Table 3.10 reveals that the reactive power output of the sources calculated by distribution factor methods are closer to those obtained by the NRLF method.

3.5.2 IEEE 30-bus System

For this system, results of only four outage cases have been presented. These cases include the outage of

(1) a line between bus-2 and bus-5 whose pre-outage real power flow was the second largest amongst all transmission lines. The maximum real power flow was in a line between bus-1 and bus-2, but it has not been considered as the post-outage NRLF did not converge for this case.

(2) a line between bus-5 and bus-12 whose pre-outage reactive power flows were Q_{5-12} = 20.6 and Q_{12-5} = -14.2 MVARs. This line carries reactive power which is second largest amongst all the lines. The largest reactive power flow was in the line (1-2).

(3) a transformer between bus-10 and bus-28 whose complex power flow, S_{10-28} = 24.1 MVA, was the highest amongst all the transformers, and

Table 3.9: 14-bus system– Post-outage bus voltage magnitudes

Bus No.	Outages of											
	line (2-4)			line (5-6)			Transformer (9-6)			Gen-2		
	V^{PF}	V^{DF}	ϵ^V	V^{PF}	V^{DF}	ϵ^V	V^{PF}	V^{DF}	ϵ^V	V^{PF}	V^{DF}	ϵ^V
1	1.060	1.060	0.000	1.060	1.060	0.000	1.060	1.060	0.000	1.060	1.060	0.000
2	1.045	1.039	0.006	1.045	1.045	0.000	1.045	1.045	0.000	1.032	1.022	0.010
3	1.066	1.055	0.011	1.066	1.069	0.003	1.070	1.073	0.003	1.076	1.050	0.026
4	0.966	0.973	0.007	1.010	1.010	0.000	1.010	1.009	0.001	1.021	0.988	0.023
5	1.090	1.074	0.016	1.090	1.115	0.025	1.090	1.098	0.008	1.090	1.070	0.020
6	1.055	1.047	0.008	1.039	1.063	0.024	1.068	1.072	0.004	1.064	1.043	0.021
7	1.047	1.040	0.007	1.038	1.056	0.018	1.055	1.061	0.006	1.058	1.035	0.023
8	1.017	1.016	0.001	1.025	1.029	0.004	1.026	1.029	0.003	1.027	1.011	0.016
9	1.008	1.009	0.001	1.019	1.024	0.005	1.021	1.024	0.003	1.023	1.005	0.018
10	1.042	1.034	0.008	1.035	1.051	0.016	1.049	1.056	0.007	1.053	1.030	0.023
11	1.051	1.041	0.010	1.047	1.056	0.009	1.055	1.060	0.005	1.061	1.036	0.025
12	1.051	1.040	0.011	1.050	1.055	0.005	1.055	1.059	0.004	1.061	1.035	0.026
13	1.045	1.035	0.010	1.044	1.050	0.006	1.049	1.054	0.005	1.055	1.030	0.025
14	1.028	1.019	0.009	1.023	1.035	0.012	1.034	1.040	0.006	1.039	1.015	0.024

Table 3.10: 14-bus system– Post-outage reactive power output of sources

Bus No.	Outages of							
	line (2-4)		line (5-6)		Transformer (9-6)		Gen-2	
	Q^{PF}	Q^{DF}	Q^{PF}	Q^{DF}	Q^{PF}	Q^{DF}	Q^{PF}	Q^{DF}
1	-0.1080	0.0056	-0.1517	0.0009	-0.1556	-0.1611	0.0438	0.2289
2	0.2642	0.3650	0.3674	0.3061	0.3453	0.3061	0.0000	0.0000
3	0.2401	0.1899	0.2401	0.1899	0.1769	0.1981	0.2271	0.1894
4	0.4000	0.2219	0.2349	0.1984	0.2201	0.1985	0.3196	0.1984
5	0.2147	0.1620	0.0000	0.0000	0.1352	0.1620	0.1797	0.1620

(4) a generator at bus-2 whose real power generation was 40 MW and reactive power generation was 50 MVAR in the pre-outage condition.

The post-outage bus voltage magnitudes for all these cases, calculated by the distribution factors method and the load flow method are given in Table 3.11 and the reactive power output of sources in Table 3.12.

Table 3.11 shows that maximum errors in bus voltage magnitude for the above four outage cases are 0.062 pu, 0.003 pu, 0.058 pu, 0.034 pu, respectively. From Table 3.12, it can be seen that maximum errors in reactive power output of sources are relatively higher in all the contingency cases.

3.5.3 75-bus UPSEB System

75-bus UPSEB system consists of 114 lines (400 kV and 220 kV), 32 transformers (including 15 generating transformers) and 15 generators. Outage of a generating transformer is same as outage of the generating unit. For this system, the results of only two outage cases have been presented in Table 3.13 and 3.14 corresponding to the,

(1) outage of a line between bus-41 (Singrauli) and bus-42 (Rihand-STS), whose pre-outage real power flow (P_{41-42} = 445.90 MW) was the largest amongst all the transmission lines and

(2) outage of a 400 kV line between bus-41 and bus-35 (Anpara), whose reactive power flow (Q_{41-35} = 105.7 MVAR and Q_{35-41} = -113.0 MVAR) was the largest amongst all the transmission lines. The real power flow in this line was 184.0 MW.

Table 3.13 shows that the maximum bus voltage magnitude error is 0.024 pu at bus-6 in the case of line (41-42) outage and it is only 0.011 pu at bus-15 in the case of line (41-35) outage. The reactive power output of the sources, calculated by distribution factors method and load flow method, are given in Table 3.14.

3.5.4 Change in the System Loading

Further, it was felt worth exploring the accuracy of predicting post-outage states for change in the system loading using the same distribution factors computed at a base loading. A typical case pertaining to the outage of line (2-4) in IEEE 14-bus system has

Table 3.11: 30-bus system– Post-outage bus voltage magnitudes

Bus No.	Outages of line (2-5)			line (5-12)			Transformer (10-28)			Gen-2		
	V^{PF}	V^{DF}	ϵ^V	V^{PF}	V^{DF}	ϵ^V	V^{PF}	V^{DF}	ϵ^V	V^{PF}	V^{DF}	ϵ^V
1	1.060	1.060	0.000	1.060	1.060	0.000	1.060	1.060	0.000	1.060	1.060	0.000
2	1.040	1.037	0.003	1.043	1.043	0.000	1.044	1.044	0.000	1.021	1.012	0.009
3	0.986	0.991	0.005	1.010	1.007	0.003	1.010	1.008	0.002	1.010	0.980	0.030
4	1.056	1.063	0.007	1.082	1.079	0.003	1.082	1.084	0.002	1.080	1.052	0.028
5	0.908	0.970	0.062	1.010	1.010	0.000	1.010	1.009	0.001	0.999	0.977	0.022
6	1.055	1.053	0.002	1.071	1.068	0.003	1.071	1.074	0.003	1.071	1.041	0.030
7	1.010	1.020	0.010	1.039	1.037	0.002	1.039	1.041	0.002	1.036	1.009	0.027
8	0.994	1.004	0.010	1.023	1.021	0.002	1.024	1.027	0.003	1.020	0.992	0.028
9	1.023	1.027	0.004	1.045	1.043	0.002	1.045	1.048	0.003	1.042	1.015	0.027
10	1.046	1.057	0.011	1.078	1.076	0.002	1.035	1.091	0.056	1.074	1.045	0.029
11	0.989	0.999	0.010	1.014	1.012	0.002	1.012	1.014	0.002	1.007	0.987	0.020
12	0.937	0.974	0.037	0.994	0.997	0.003	1.001	1.001	0.000	0.994	0.971	0.023
13	0.979	0.991	0.012	1.009	1.007	0.002	1.008	1.009	0.001	1.004	0.981	0.023
14	1.007	1.012	0.005	1.030	1.028	0.002	1.030	1.034	0.004	1.028	1.000	0.028
15	1.002	1.007	0.005	1.026	1.023	0.003	1.023	1.030	0.007	1.023	0.995	0.028
16	1.003	1.010	0.007	1.028	1.026	0.002	1.029	1.032	0.003	1.025	0.998	0.027
17	0.991	1.000	0.009	1.019	1.017	0.002	1.020	1.023	0.003	1.016	0.988	0.028
18	0.986	0.993	0.005	1.013	1.010	0.003	1.011	1.017	0.006	1.009	0.981	0.028
19	0.981	0.986	0.005	1.008	1.006	0.002	1.007	1.012	0.005	1.005	0.976	0.029
20	0.983	0.991	0.008	1.011	1.009	0.002	1.011	1.015	0.004	1.008	0.980	0.028
21	0.985	0.995	0.010	1.014	1.012	0.002	1.013	1.019	0.006	1.011	0.983	0.028
22	0.987	0.996	0.009	1.016	1.014	0.002	1.014	1.021	0.007	1.012	0.984	0.026
23	0.993	1.000	0.007	1.020	1.017	0.003	1.012	1.024	0.012	1.016	0.988	0.028
24	0.991	1.000	0.009	1.020	1.018	0.002	1.006	1.025	0.019	1.016	0.988	0.028
25	1.019	1.030	0.011	1.051	1.048	0.003	1.015	1.061	0.046	1.047	1.018	0.029
26	1.002	1.013	0.011	1.033	1.031	0.002	0.998	1.044	0.046	1.030	0.997	0.033
27	1.001	1.010	0.009	1.022	1.021	0.001	1.021	1.022	0.001	1.016	1.001	0.015
28	0.982	0.992	0.010	1.011	1.009	0.002	1.010	1.009	0.001	1.007	0.977	0.030
29	1.026	1.038	0.012	1.059	1.057	0.002	1.015	1.073	0.058	1.055	1.021	0.034
30	1.015	1.027	0.012	1.048	1.046	0.002	1.004	1.062	0.058	1.044	1.010	0.034

Table 3.12: 30-bus system– Post-outage reactive power output of sources

Bus No.	Outages of line (2-5) Q^{PF}	line (2-5) Q^{DF}	line (5-12) Q^{PF}	line (5-12) Q^{DF}	Transformer (10-28) Q^{PF}	Transformer (10-28) Q^{DF}	Gen-2 Q^{PF}	Gen-2 Q^{DF}
1	0.0331	0.0493	-0.1320	-0.1282	-0.1378	-0.1452	0.2028	0.4691
2	0.5000	0.5548	0.5000	0.5000	0.5000	0.5001	0.0000	0.0000
3	0.4000	0.1991	0.2467	0.1988	0.2568	0.1989	0.3637	0.1991
4	0.2400	0.2279	0.2325	0.2280	0.2341	0.2280	0.2400	0.2279
5	0.4000	0.4278	0.3171	0.4906	0.3769	0.3625	0.4000	0.3622
6	0.2400	0.1943	0.1992	0.1944	0.1965	0.1944	0.2197	0.1943

been presented. The increase in system loading was restricted to 25% because load flow did not converge for higher than 125% of base case loading. However, loading has been decreased up to 50% from their base values. The real and reactive power loading were changed in same ratio, at all the buses, simultaneously, to simulate the above conditions. The comparison of voltage predicted using the proposed distribution factors and the full AC load flow method for 125%, 115% and 50% of the base loading are given in Table 3.15. The voltage magnitudes (V^{DF_2}) obtained by the distribution factors presented in references [118, 138] based on only reactive power flow in the line or reactive power generation of sources are also presented in Table 3.15 for the same loading (150%, 115% and 50% of the base case) and line outage (i.e. line between bus-2 and 4).

It can be observed from this table that the maximum errors with the proposed method are 0.126 pu, 0.061 pu and 0.005 pu for the three loading cases and with the distribution factors proposed in references [118, 138] are 0.249, 0.131, 0.039 pu, respectively. This reveals that the proposed sets of distribution factors are more accurate than those suggested in references [118, 138]. The accuracy, however, decreases for increase in loading. Since the distribution factors are able to predict voltages with almost same accuracy for load variation by −50% to +15% around the operating point at which they have been computed, they need not be recomputed for change in the system loading in this range.

3.5.5 Solution Time

From the results presented in previous sections and Chapter 2, it can be observed that the proposed distribution factors are able to predict post-outage voltages with slightly

Table 3.13: 75-bus system– Post-outage bus voltage magnitudes

Bus No.	Outages of line (41-42)			Outages of line (35-41)		
	V^{PF}	V^{DF}	ϵ^V	V^{PF}	V^{DF}	ϵ^V
1	1.030	1.030	0.000	1.030	1.030	0.000
2	1.033	1.044	0.011	1.042	1.042	0.000
3	1.022	1.032	0.010	1.030	1.030	0.000
4	1.058	1.052	0.006	1.049	1.049	0.000
5	1.067	1.054	0.013	1.050	1.050	0.000
6	1.070	1.054	0.024	1.050	1.050	0.000
7	1.074	1.054	0.020	1.050	1.050	0.000
8	1.041	1.040	0.001	1.039	1.037	0.002
9	1.071	1.050	0.021	1.050	1.048	0.002
10	1.020	1.022	0.002	1.020	1.020	0.000
11	1.042	1.021	0.020	1.020	1.019	0.001
12	1.046	1.050	0.004	1.050	1.051	0.001
13	1.050	1.050	0.000	1.050	1.051	0.001
14	1.052	1.034	0.018	1.030	1.020	0.000
15	1.010	1.002	0.008	1.010	0.999	0.011
16	1.009	1.020	0.011	1.018	1.018	0.000
17	1.019	1.025	0.006	1.022	1.024	0.002
18	1.000	1.011	0.011	1.010	1.009	0.001
19	0.987	0.995	0.008	0.995	0.994	0.001
20	0.990	0.989	0.001	0.988	0.987	0.001
21	1.016	1.011	0.004	1.007	1.007	0.000
22	1.020	1.021	0.001	1.017	1.017	0.000
23	1.000	1.010	0.010	1.006	1.009	0.003
24	0.992	1.001	0.009	0.999	0.999	0.000
25	1.012	1.009	0.003	1.006	1.006	0.000
26	0.977	0.990	0.013	0.988	0.989	0.001
27	0.977	0.990	0.013	0.988	0.988	0.000
28	1.022	1.016	0.006	1.013	1.012	0.001
29	1.027	1.025	0.002	1.021	1.021	0.000
30	1.019	1.014	0.005	1.010	1.010	0.000
31	1.053	1.041	0.011	1.037	1.037	0.000
32	1.052	1.040	0.012	1.036	1.036	0.000
33	1.053	1.042	0.011	1.037	1.038	0.001
34	1.010	1.009	0.001	1.008	1.006	0.002
35	1.028	1.032	0.004	1.025	1.030	0.005
36	0.986	0.994	0.008	0.993	0.993	0.000
37	0.965	0.974	0.009	0.973	0.973	0.000

Contd. ...

Table 3.13 (Contd.) ...

Bus No.	Outages of line (41-42) V^{PF}	V^{DF}	ϵ^V	line (35-41) V^{PF}	V^{DF}	ϵ^V
38	1.039	1.036	0.003	1.032	1.032	0.000
39	1.040	1.031	0.009	1.027	1.027	0.000
40	1.006	0.995	0.011	0.994	0.993	0.001
41	1.029	1.036	0.007	1.038	1.038	0.000
42	1.043	1.037	0.006	1.038	1.038	0.000
43	1.030	1.021	0.009	1.017	1.017	0.000
44	1.019	1.014	0.005	1.018	1.011	0.007
45	1.031	1.030	0.001	1.031	1.027	0.004
46	0.967	0.977	0.010	0.976	0.975	0.001
47	0.989	1.001	0.011	1.001	1.000	0.001
48	0.989	0.977	0.012	0.977	0.976	0.001
49	0.979	0.967	0.012	0.966	0.965	0.001
50	0.967	0.983	0.016	0.984	0.981	0.003
51	0.966	0.978	0.012	0.975	0.976	0.001
52	0.966	0.978	0.012	0.976	0.976	0.000
53	1.018	1.011	0.007	1.007	1.007	0.000
54	1.001	1.001	0.000	1.000	0.998	0.002
55	0.993	0.988	0.005	0.989	0.985	0.004
56	1.021	1.014	0.007	1.010	1.010	0.000
57	1.008	1.001	0.007	0.997	0.997	0.000
58	1.010	1.002	0.008	0.998	0.998	0.000
59	1.010	1.003	0.007	0.999	0.999	0.000
60	0.997	0.994	0.003	0.991	0.991	0.000
61	1.020	1.013	0.007	1.009	1.009	0.000
62	1.034	1.024	0.010	1.020	1.020	0.000
63	0.994	0.992	0.002	0.991	0.988	0.003
64	0.972	0.971	0.001	0.970	0.969	0.001
65	1.016	1.011	0.005	1.007	1.007	0.000
66	0.979	0.977	0.002	0.977	0.976	0.001
67	0.990	1.000	0.010	0.998	0.998	0.000
68	0.990	1.002	0.008	1.000	1.000	0.000
69	0.939	0.949	0.010	0.947	0.947	0.000
70	0.996	0.993	0.003	0.989	0.989	0.000
71	0.978	0.989	0.011	0.988	0.988	0.000
72	0.997	0.995	0.002	0.991	0.991	0.000
73	1.027	1.028	0.001	1.029	1.025	0.004
74	1.001	1.011	0.009	1.007	1.009	0.002
75	1.029	1.027	0.002	1.023	1.024	0.001

Table 3.14: 75-bus system– Post-outage reactive power output of sources

Bus No.	Outages of line (41-42) Q^{PF}	line (41-42) Q^{DF}	line (35-41) Q^{PF}	line (35-41) Q^{DF}
1	1.5800	0.3740	0.4176	0.4715
2	0.9600	0.9600	0.9600	0.9600
3	0.8300	0.7781	0.5681	0.7781
4	0.5894	0.6000	0.3749	0.6000
5	0.2643	0.2744	0.1444	0.2744
6	0.1470	0.1528	0.0911	0.1528
7	0.1195	0.1072	0.0393	0.1072
8	0.6800	0.6800	0.6441	0.6800
9	2.0749	1.0876	1.3451	1.0876
10	0.5600	0.4123	0.2288	0.4123
11	0.9438	0.6869	0.5431	0.6861
12	3.4400	2.8539	2.3784	2.8539
13	1.0420	1.3843	1.2270	1.3842
14	0.4512	0.5087	0.0761	0.5081
15	-0.300	-0.300	-0.300	-0.300

Table 3.15: 14-bus system– Bus voltages for different loading

Bus No.	1.25 pu V^{PF}	V^{DF}	V^{DF_2}	1.15 pu V^{PF}	V^{DF}	V^{DF_2}	0.50 pu V^{PF}	V^{DF}	V^{DF_2}
1	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060
2	1.016	1.027	1.052	1.036	1.035	1.049	1.045	1.044	1.036
3	0.969	1.030	1.081	1.023	1.046	1.075	1.070	1.065	1.048
4	0.825	0.951	1.074	0.902	0.963	1.033	1.010	1.010	0.971
5	0.999	1.065	1.120	1.053	1.069	1.100	1.090	1.085	1.066
6	0.957	1.025	1.082	1.013	1.036	1.069	1.076	1.073	1.054
7	0.940	1.010	1.069	1.000	1.025	1.059	1.077	1.073	1.053
8	0.944	0.995	1.069	0.986	1.007	1.033	1.040	1.038	1.023
9	0.922	0.986	1.041	0.970	0.998	1.030	1.036	1.035	1.017
10	0.934	1.003	1.042	0.994	1.020	1.053	1.072	1.068	1.048
11	0.946	1.012	1.067	1.004	1.029	1.060	1.069	1.065	1.046
12	0.948	1.010	1.063	1.005	1.028	1.058	1.064	1.059	1.042
13	0.940	1.003	1.057	0.998	1.022	1.052	1.062	1.057	1.040
14	0.914	0.983	1.041	0.977	1.002	1.035	1.062	1.057	1.038

Table 3.16: Comparison of CPU time (in seconds)

System	Linearized load flow method (version A_3)	Distribution factors method	
		Calculation of DFs	Post-outage Calculation
14-bus	2.76	0.39	0.12
30-bus	13.33	1.57	0.23
75-bus	199.68	32.70	0.61

less accuracy as compared to the linearized load flow models. For example, the maximum error in prediction of post-outage voltages in case of severe outage in the three systems is 6.82% by using the distribution factors whereas this value is 4.97% by using the linearized load flows. The CPU time required to compute the post-outage voltages using both the methods were recorded on HP 9000/850 computer and have been given in Table 3.16 for the three test systems. The CPU time given in this table is the total time required to analyze 23, 43 and 104 contingencies in 14-bus, 30-bus and 75-bus systems, respectively. Column-3 of Table 3.16 provides the CPU time required to calculate all the eight sets of distribution factors at the base operating point for each of the three systems. This does not include the time required to run the base load flow. Column-4 shows the total CPU time required to determine the post-outage voltages and reactive powers for all the contingencies in the three systems using the already computed distribution factors. From Table 3.16, it can be seen that the proposed distribution factors method takes considerably less CPU time as compared to the linearized load flow models.

3.6 Conclusions

In this Chapter, new sets of voltage and reactive power distribution factors, for both line and generator outages have been developed and computed by utilizing the network sensitivity. The distribution factors can be pre-calculated at a base operating point and can be stored for the use in outage analysis. The contingency studies conducted on the three samples systems reveal that

(i) The prediction of the post-outage bus voltages using the new distribution factors are quite accurate and provides the results with a maximum error of 3.23% in IEEE 14-bus system, 6.82% in IEEE 30-bus system and 2.24% in the UPSEB 75-bus system

for outage of heavily loaded lines. However, with the use of distribution factors, the error in predicting the reactive power output of sources is slightly higher.

(ii) Since the distribution factors are obtained directly from a base load flow result, without involving any additional load flow for simulation of outages, its calculation and updating is quite fast and can be applied to on-line monitoring of voltage security of the system at control centers.

(iii) The set of distribution factors computed at a base loading accurately predicts the post-outage voltages of the system even for small change in system loading. Thus, they need not be recomputed for small deviation in the loading. This will further reduce the computational time for the voltage contingency analysis.

(iv) The proposed distribution factors defined with respect to both pre-outage real and reactive powers of the elements, predict the post-outage voltages of the system more accurately than the distribution factors proposed in references [118, 138] defined in terms of only reactive powers under different loading conditions.

(v) The proposed distribution factors computes the bus voltages with slightly less accuracy as compared to the linearized load flow models suggested in Chapter 2. However, the post-outage calculations using distribution factors are much faster as compared to the linearized load flows.

Chapter 4

Contingency Selection Algorithm for Voltage/Reactive Power Security Analysis

4.1 Introduction

Contingency selection is carried out for quickly identifying those contingencies which may cause out-of-limit violations so as to reduce the number of contingencies that need to be analyzed by full AC load flow while assessing the power system's security. Two popularly used methods for contingency selection are: *ranking methods* and *screening methods.*

Ranking methods involve ranking of contingencies in approximate order of severity. Contingencies are ranked based on the value of a scalar performance index (PI) which measures the system stress in some manner. For example, contingencies could be ranked for voltage problems using a PI defined as the sum of the squared voltage deviations [18,24] from their specified values. Several PI based methods have been suggested and tested for voltage security analysis [18, 36, 75, 82]. In ranking method, the performance indices are explicitly expressed in terms of network variables and are directly evaluated. It does not require computation of post-outage quantities, which are evaluated in the screening methods by using some approximate solution approach.

Screening methods use approximate network solutions to identify cases causing limit violations. The network monitored quantities are first calculated for all the contingencies. Ranking is done based on the results of the approximate solutions. Some of the methods

used to find approximate solution along with screening methods are the distribution factors [38, 118], DC load flow [64], linearized load flow, one iteration of AC load flow [30], local solution methods [20, 80] etc.

Most of the work on contingency selection algorithm utilizes the second order performance indices which, in general, suffers from masking and misranking effects. Some of the efforts in reducing these effects include the works of Halpin et al. [39] and Schafer et al. [90]. The method suggested in reference [39] uses an optimization technique based on probabilistic approach to compute threshold value of PI to capture critical contingencies and optimal weights of the second order performance index.

In this Chapter, various existing performance indices for Voltage/ Reactive power contingency selection have been critically examined. A new method for optimal selection of weights have been suggested along with higher order performance indices which eliminates misranking and masking effects. The distribution factors calculated in Chapter 3 have been utilized to compute post-contingency quantities (voltage magnitudes and reactive power output of sources). The proposed algorithm have been tested on IEEE 14-bus, IEEE 30-bus and 75-bus UPSEB systems.

4.2 Existing Voltage and Reactive Power Performance Indices

Ejebe et al. [18] suggested in 1979 the use of performance indices for ranking of contingencies according to their relative severities for both line and voltage security analysis. Various modified versions of ranking methods for voltage contingency selection have been suggested by Lauby et al. [36], Albuyeh et al. [28], Medicherla et al. [30] and Wasley et al. [32]. The performance indices, in general form, can be written as

$$PI = \sum_i \frac{W_i}{2n}[f_i(\underline{z})]^{2n} \tag{4.1}$$

where $f_i(\underline{z})$ is a linear function of z_i which denotes the changes in bus voltage magnitudes or generator bus injections with respect to their ratings etc. The order of the above performance index in $2n$.

A brief description of some of the existing methods and performance indices used for voltage and reactive power contingency selection are presented below.

Method-1

The Tellegan theorem together with the adjoint network concept has been used by Ejebe and Wollenberg [18] to derive the sensitivity of a voltage performance index with respect to contingencies. The voltage performance index was defined as

$$PI^v = \sum_{i=1}^{N} \frac{\alpha_i}{2}\left(\frac{\Delta V_i}{\Delta V_i^{lim}}\right)^2 \tag{4.2}$$

where

$$\begin{aligned}
\Delta V_i &= V_i - V_i^{sp} \\
\Delta V_i^{lim} &= \tfrac{V_i^{max} - V_i^{min}}{2} \\
V_i &= \text{post-outage bus voltage magnitude at bus-}i \\
\alpha_i &= \text{user selected weighting factor (usually taken as 1)} \\
V_i^{sp} &= \text{specified (rated) voltage magnitude at bus-}i.
\end{aligned}$$

The reactive power performance index was defined as

$$PI^q = \sum_{i=1}^{N_q} \frac{\alpha_i}{2}\left(\frac{Q_{Gi}}{Q_{Gi}^{max}}\right)^2 \tag{4.3}$$

where

$$\begin{aligned}
Q_{Gi} &= \text{post-outage reactive power produced at bus-}i \\
Q_{Gi}^{max} &= \text{maximum reactive power production limit at bus-}i.
\end{aligned}$$

Method-2

This method, suggested by Albuyeh et al. [28], utilizes the first iteration of an AC load flow to compute the following performance indices for each contingency.

$$PI^v = \sum_{i \in S_1} W_{vi} \frac{|V_i - V_i^{lim}|}{V_i^{lim}} \tag{4.4}$$

and

$$PI^q = \sum_{i \in S_2} W_{qi} \frac{|Q_{Gi} - Q_{Gi}^{lim}|}{Q_{Gi}^{lim}} \tag{4.5}$$

where

$$V_i^{lim} = \begin{cases} V_i^{max} & \text{if } V_i > V_i^{max} \\ V_i^{min} & \text{if } V_i < V_i^{min} \end{cases}$$

$$Q_{Gi}^{lim} = \begin{cases} Q_{Gi}^{max} & \text{if } Q_{Gi} > Q_{Gi}^{max} \\ Q_{Gi}^{min} & \text{if } Q_{Gi} < Q_{Gi}^{min} \end{cases}$$

S_1 is the set of all buses at which bus voltage security limits are violated and S_2 is the set of (source) buses at which the MVAR generation security limits are violated. W_{vi} and W_{qi} are the voltage and MVAR weighting factors for bus-i.

Method-3

Medicherla et al. [30] suggested a method which uses the *load curtailment* concept to achieve the pre-contingency voltage level. The voltage performance index using this concept has been defined as

$$PI^v = \left[\left(\sum_{i=1}^{N} \left| \frac{2P_{Li}\Delta V_i}{V_i^o} \right| \right)^2 + \left(\sum_{i=1}^{N} \left| \frac{2Q_{Li}\Delta V_i}{V_i^o} \right| \right)^2 \right]^{1/2} \tag{4.6}$$

where P_{Li} is the MW load at bus-i (assumed constant), Q_{Li} the MVAR load at bus-i (assumed constant), V_i^o the pre-contingency voltage magnitude at bus-i and ΔV_i the change in the voltage magnitude at bus-i caused by a contingency. The performance index has been computed utilizing approximate network solution obtained from the first iteration of fast decoupled load flow for each contingency.

Method-4

This method, suggested by Wasley et al. [32], simulates each contingency by the first iteration of an AC load flow. The performance indices have been defined as

$$PI^v = \sum_{i \in S_1} W_{vi} \Delta V_i^2 \tag{4.7}$$

and

$$PI^q = \sum_{i \in S_2} W_{qi} \Delta Q_i^2 \tag{4.8}$$

where $\Delta V_i = (\Delta V_i^{nom} / \Delta V_i^{lim}) - 1$ is the distance of the operating point from the nearest boundary of violated bus voltage security region and

$$\begin{aligned} \Delta V_i^{nom} &= V_i - V_i^{nom} \\ V_i^{nom} &= (V_i^{max} + V_i^{min})/2 \\ \Delta V_i^{lim} &= (V_i^{max} - V_i^{min})/2 \end{aligned}$$

$\Delta Q_i = (\Delta Q_i^{nom} / \Delta Q_i^{lim}) - 1$ is the distance from the nearest boundary of the violated bus MVAR generation security region and

$$\begin{aligned}
\Delta Q_i^{nom} &= Q_i - Q_i^{nom} \\
Q_i^{nom} &= (Q_i^{max} + Q_i^{min})/2 \\
\Delta Q_i^{lim} &= (Q_i^{max} - Q_i^{min})/2
\end{aligned}$$

Method-5

In this method, proposed by Lauby et al. [36], the post-contingency line MW (real power) flows are computed by DC load flow and these are used to compute the following performance index for each contingency.

$$PI^v = \sum_{l=1}^{N_l} W_l X_l \left(\frac{1}{P_{0i}^2} + \frac{1}{P_{0j}^2} \right)^{\frac{1}{4}} P_l^2 \tag{4.9}$$

where

W_l = circuit weighting factor (1 or 0)

X_l = reactance of circuit-l

P_l = real power flow on circuit-l

P_{0i} and P_{0j} are non-linear function of ΔQ_i and ΔQ_j, respectively where i and j are the sending end and receiving end buses of line-l and

$$\Delta Q_i = \frac{B_{shl}}{2} + \frac{X_l}{\sum_{k \in S_i} X_k} Q_i \tag{4.10}$$

$$\Delta Q_j = \frac{B_{shl}}{2} + \frac{X_l}{\sum_{k \in S_j} X_k} Q_j \tag{4.11}$$

B_{shl} is the charging susceptance of line-l, S_i the set of all lines connected at the bus-i and S_j the set of all lines connected at bus-j. Q_i is the net maximum reactive power injection at bus-i.

$$Q_i = (Q_{gen})\text{max} + Q_{\text{shunt cap.}} - Q_{\text{load}} - Q_{\text{shunt reactors}} \tag{4.12}$$

Method-6

Lo et al. [75] suggested a method to compute the bus voltage change by modifying the reactance matrix for each contingency. The voltage performance index was defined as

$$PI^v = \sum_{i=1}^{N} W_{vi} \left[\frac{(V_i^o + \Delta V_i - V_i^{nom})}{\frac{V_i^{max} - V_i^{min}}{2}} \right]^2 \tag{4.13}$$

where

$$\begin{array}{lcl} \Delta V_i & = & \frac{(X_{is}-X_{ir})X_k}{(X_k-X_{kk})} I_k \text{ for line-}k \text{ outage} \\ X_{is} & = & \text{element of bus reactance matrix } [X] \ (=[\mathrm{B}]^{-1}) \\ X_k & = & \text{reactance of line-}k \\ V_i^o & = & \text{base case voltage at bus-}i \\ I_k & = & \text{pre-outage current in line-}k \end{array}$$

Method-7

This method, suggested by Nara et al. [43], defines a voltage performance index which considers two types of limits of voltages for each bus-i.

Alarm limits : V_i^{amax} and V_i^{amin}

Security limits : V_i^{max} and V_i^{min}

The performance index has been defined as

$$PI^v = \sum_{i=1}^{N} \left(\frac{d_i^{max}}{a_i^{max}} \right)^2 + \sum_{i=1}^{N} \left(\frac{d_i^{min}}{a_i^{min}} \right)^2 \tag{4.14}$$

where

$$d_i^{max} = \begin{cases} \left(\frac{V_i - V_i^{amax}}{V_i^{nom}} \right) & \text{if } V_i > V_i^{amax} \\ 0 & \text{other wise} \end{cases}$$

$$d_i^{min} = \begin{cases} \left(\frac{V_i^{amin} - V_i}{V_i^{nom}} \right) & \text{if } V_i < V_i^{amin} \\ 0 & \text{other wise} \end{cases}$$

$$\begin{array}{lcl} a_i^{max} & = & (V_i^{max} - V_i^{amax})/V_i^{nom} \\ a_i^{min} & = & (V_i^{amin} - V_i^{min})/V_i^{nom} \\ V_i^{nom} & = & (V_i^{max} + V_i^{min})/2 \end{array}$$

Method-8

The change in bus voltage magnitudes, as suggested by Dabbaghchi et al. [46], have been computed by using coefficient matrices of the fast decoupled load flow method. The voltage performance index for each contingency has been defined as

$$PI^v = \sum_{i=1}^{N} \left[\frac{(V_i^o + \Delta V_i - V_i^{nom})}{\frac{V_i^{max} - V_i^{min}}{2}} \right]^2 \tag{4.15}$$

where ΔV_i is the change in bus voltage magnitude at bus-i in the event of contingency and has been calculated using FDLF equations.

Method-9

The performance index for a contingency case has been formulated by Chen et al. [82] in such a way that detailed knowledge of post-contingency voltage is not required. The PI for post-contingency voltage change has been defined as

$$PI = \sum_{i=1}^{N} \frac{W_{vi}}{2} \left[\frac{(V_i^o + \Delta V_i - V_i^{nom})}{\frac{V_i^{max} - V_i^{min}}{2}} \right]^2 \tag{4.16}$$

The change in PI due to outage from base-case has been computed as

$$\Delta PI = PI - PI^o = \sum_{i=1}^{N} [\beta_i \Delta V_i + \gamma_i \Delta V_i^2] \tag{4.17}$$

where β_i and γ_i are the constants and ΔV_i is calculated using FDLF equations.

Method-10

This method, proposed by Schafer et al. [90], uses the following extended definition of the PI based on a vector norm formulation.

$$PI^v = \left[\sum_{i=1}^{N} W_i \left| \frac{\Delta V_i}{\Delta V_i^{max}} \right|^m \right]^{\frac{1}{m}} \tag{4.18}$$

where m is the exponent of PI and has been taken as large value ($m = 20$) in order to avoid the masking effect.

4.3 Proposed Voltage and Reactive Power Performance Indices

Two sets of performance indices have been considered, in the present work, to measure the relative severity of contingencies in terms of their effect on voltage levels and reactive power output of the sources. The voltage performance index (PI^v), chosen to quantify system deficiency to out-of-limit-bus voltages, is defined as

$$PI^v = \sum_{i=1}^{N} \frac{W_{vi}}{2n} \left(\frac{(V_i - V_i^{sp})}{\Delta V_i^{lim}} \right)^{2n} \tag{4.19}$$

where V_i and V_i^{sp} are the post-outage voltage magnitude and specified (rated) voltage magnitude, respectively at bus-i, n is the exponent of the function and N is the total number of buses in the system. W_{vi} is the weighting factor and

$$\Delta V_i^{lim} = \frac{V_i^{max} - V_i^{min}}{2} \tag{4.20}$$

Any contingency case with voltage levels outside the limit yields a high value of PI^v. On the other hand, when all voltages are within the limit, the voltage performance index PI^v is small. Thus, this index measures the severity of the out-of-limit bus voltages, and for a set of contingencies, this index provides a direct means of comparing the relative severity of the different outages.

Since the bus voltage levels depend mainly on reactive power flows and, therefore, on the reactive power production of the generators and other power sources, the reactive power output of sources can also be used as the measure of voltage contingency selection. In view of this, a reactive power performance index (PI^q) has been defined

$$PI^q = \sum_{i=1}^{N_q} \frac{W_{qi}}{2n} \left(\frac{(Q_{Gi} - Q_{Gi}^{sp})}{\Delta Q_{Gi}^{lim}} \right)^{2n} \tag{4.21}$$

where

$$\Delta Q_{Gi}^{lim} = \frac{(Q_{Gi}^{max} - Q_{Gi}^{min})}{2} \tag{4.22}$$

Q_{Gi} is the reactive power output of the source-i. N_q is the total number of reactive power sources and n the exponent of the function, and

$$Q_{Gi}^{sp} = \frac{(Q_{Gi}^{max} + Q_{Gi}^{min})}{2} \tag{4.23}$$

In the above expressions Q_{Gi}^{max} and Q_{Gi}^{min} are the maximum and minimum reactive power output limits of the source-i. The contingency, in which the reactive power generation of the sources deviate from the specified values, results in greater value of PI^q.

The exponent n in the definition of the two performance indices PI^v and PI^q, given by equations (4.19) and (4.21), have been varied from 1 to 10 to explore its desired value or the order of the performance indices, which minimizes the *masking effect*. In order to eliminate the *misranking effects*, the proper selection of weights is required. A simple and efficient scheme has been suggested in this Chapter, which is described in section 4.4.

4.4 Calculation of Optimal Weights

The misranking of contingencies are mainly caused due to the inaccuracies in computing post-contingency states of the system [18, 118]. In the proposed contingency selection method, distribution factors as described in Chapter 3, have been used to calculate

the post-contingency states of the system. The proper selection of weights in PI based methods is very important in eliminating the misranking effect [39]. Some approximate guidelines for selecting the weights are reviewed in references [39,118]. However, a proper attempt has only been mode by Halpin et al. [39] who used an optimization technique to compute the weights. Their method maximizes the capture rate and minimizes false alarm rate, both formulated as probabilistic functions. The method, in general, is complex and difficult to be adopted by utilities. Hence, a simple approach has been proposed in this section, for optimal selection of weights. It is based on the concept of tuning the weights (with their minimum possible values) such that the relative severity of contingencies predicted along with the approximate distribution factors (DFs) method matches with the full AC power flow (PF) method. The method utilizes minimization of an objective function defined as the sum of the square of weights in the performance index, i.e.

$$Minimize \quad \sum_i W_i^2 \tag{4.24}$$

subject to the constraints,

$$PI_{DF}^p > PI_{DF}^q > \ldots > PI_{DF}^r \quad p,q,...,r \in N_c^c \tag{4.25}$$

and

$$PI_{DF}^r > PI_{DF}^i \quad i \in N_c^{nc} \tag{4.26}$$

where N_c^c are the critical contingencies in which the limit violations exist and N_c^{nc} are the non-critical contingencies. The $p,q,...,r^{th}$ contingencies have been arranged in equation (4.25) according to their severity order as determined by the performance indices (PI_{PF}) calculated using AC load flow method. The performance index for k^{th} contingency using distribution factors method (PI_{DF}^k) can be written as

$$PI_{DF}^k = \sum_i A_{ki} W_i \qquad \begin{array}{l} i = 2,\ldots,N \;\; for \;\; PI_{DF}^v \\ i = 1,\ldots,N_q \;\; for \;\; PI_{DF}^q \end{array} \tag{4.27}$$

The coefficient A_{ki} in the above equation can be defined from equations (4.19) and (4.21) for a selected value of n as

$$A_{ki} = \frac{1}{2n}\left(\frac{V_{i,k} - V_i^{sp}}{\Delta V_i^{lim}}\right)^{2n} \quad for \;\; voltage \;\; PI \tag{4.28}$$

$$= \frac{1}{2n}\left(\frac{Q_{Gi,k} - Q_{Gi}^{sp}}{\Delta Q_{Gi}^{lim}}\right)^{2n} \quad for \;\; reactive \;\; power \;\; PI \tag{4.29}$$

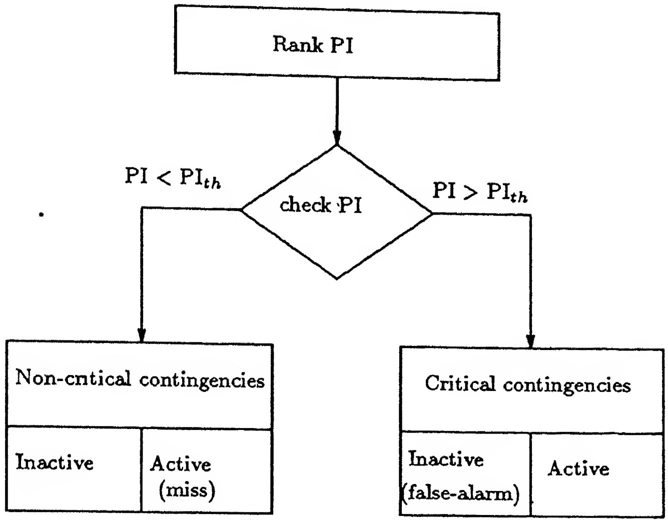

Figure 4.1: Classification of contingencies

The above equations form a standard non-linear constrained optimization problem. The optimal values of weights can be computed off-line at base operating point by solving the above optimization problem (equations (4.24) to (4.26)) for both voltage and reactive power performance indices. These values of optimal weights, then, can be used for different system loading provided it meets the required level of capture rate (CR) and false alarm rate (FR).

Capture rate (CR) and False-Alarm rate (FR)

To define the capture rate and false-alarm rate, the contingencies must be first classified as *active* (one which yields out-of-limit condition) or *inactive* (which yields no out-of-limit condition). The decision as to if a contingency is *critical* or *non-critical* is based on the value of PI and its value relative to some threshold value PI_{th}. The classification of contingencies are given in Fig. 4.1. From Fig. 4.1, there are two possible misclassification which can be made.

Miss : classifying an active contingency as being non-critical.
False-Alarm : classifying an inactive contingency as being critical.

Currently, the contingency selection algorithms are judged in terms of their capture rate (CR) [39] which is defined as

$$CR = 1 - \frac{N_m}{N_c^{nc}} \tag{4.30}$$

where N_m is the number of misses out of the N_c^{nc}, the non-critical contingencies. However, by using only CR to gauge the performance of the algorithms, one does not get the full picture since a threshold PI_{th} can be selected for CR = 1. Therefore, to complete the assessment one needs to evaluate the false-alarm rate (FR), defined as

$$FR = \frac{N_{fa}}{N_c^c} \tag{4.31}$$

where N_{fa} is the number of false-alarm out of N_c^c declared critical contingencies.

The desired value of CR and FR are one and zero, respectively. But due to inaccurate model used, for CR = 1, the value of FR may not be zero.

4.5 Results and Discussions

The effectiveness of the proposed contingency selection procedure has been tested on IEEE 14-bus, IEEE 30-bus and a practical 75-bus systems as described in Appendices-B, C and D, respectively. The maximum limit on bus voltages for the 14-bus and 30-bus systems was considered as 1.10 pu. The lower limit of bus voltages were purposely raised from 0.90 pu to 1.0 pu for IEEE 14-bus system and from 0.90 pu to 0.98 pu for IEEE 30-bus system to test the effectiveness of the proposed algorithm. The lower and upper limits of bus voltages for 75-bus system were considered as 0.95 pu and 1.07 pu, respectively. The specified voltage (V^{sp}) on the load buses were taken as average of maximum and minimum voltage limits of that bus. However, the specified voltage of generator buses were taken same as given in Appendices-B, C and D for the three systems. The specified values of reactive power generation were taken as the average of their maximum and minimum limit values. A successive quadratic programming (SQP) was used to solve the optimization problem. The results for the three test systems are given below :

4.5.1 IEEE 14-bus System

For this system, all the single line outages and single generator (except slack) outages have been considered. Thus, a total of 23 contingency cases (19 branch outages and 4 generator outages) were analyzed. The outage of line (6-5) has not been considered as it is same as the outage of generator-5, already considered in the contingency list. The

performance indices have been computed using the network solutions obtained from both the distribution factors described in Chapter 3 and an exact load flow (Newton-Raphson) method.

The voltage performance index (PI^v) have been computed for each contingency using equation (4.19) and are presented in Table 4.1 and Table 4.2 for different values of exponents (n = 1, 2, 5 and 10) using distribution factors and the exact load flow method, respectively. The reactive power performance indices (PI^q), using distribution factors method and exact load flow results have been given in Tables 4.3 and 4.4, respectively. All the weights have been considered as unity for calculation of PIs given in above tables. It is observed that with second order performance indices, some of the severe contingency cases (e.g. contingency cases L-16 and L-17 in Table 4.2) have been ranked lower than the less severe contingency cases (e.g. G-3 in Table 4.2). The masking effect has gradually reduced with the use of higher order performance indices and gets eliminated with exponent $n \geq 5$.

However, the values of performance indices computed with the distribution factors method and the exact load flow method do not match with each other even with higher exponents. They are quite different and provide different ranking to the contingencies. In order to eliminate this (misranking) problem, the optimal values of weights of the performance indices, defined in terms of results of the distribution factors method, were obtained by solving the equations (4.24) to (4.26). The voltage and reactive power performance indices have been recomputed using these optimal weights and ranking of contingencies are given in Tables 4.5 and 4.6, respectively according to their relative severity. The optimal weights associated with voltage and reactive power PIs are presented in Tables 4.7 and 4.8, respectively. The change in slack bus voltage has not been considered for contingency cases and hence, optimal weight associated with slack bus for voltage performance index is assumed to be zero.

The optimal weights computed at a base case operating point can be used for different loading of the system. To study this effect, the loading of this system was changed by $\pm 1.0\%, \pm 3.0\%$ and $\pm 5.0\%$ from the base value. The voltage based ranking, obtained from the performance index using optimal weights computed for the base case and network solution obtained for the new loading conditions with the distribution factors method (PI^v_{DF}) are given in Table 4.5. The ranking obtained by performance index using network solution obtained from the exact load flow method (PI^v_{PF}) are also included in the table

for comparison. All the weights in performance index calculation, based on exact load flow solution, were taken as unity. Only active contingency cases detected from the exact load flow method have been listed in the table. However, the list of contingencies against the distribution factors method have been truncated in order to capture all the critical cases detected by the exact method or to ensure a capture rate of 1.0. From Table 4.5, it can be seen that false alarm rate (FR) for increase in loading by 1.0%, 3.0% and 5.0% are 0.0, 1/7, 13/19, respectively. However, for decrease in loading by 1.0%, 3.0% and 5.0%, the FR values are found to be 6/12, 8/14, 15/21, respectively. Thus, for this system the optimal weights for voltage performance indices can be effectively used up to ±3.0% change in loading.

The ranking of reactive power indices for different loading, obtained from the distribution factors method along with optimal weights and exact load flow method (PI^q_{DF} and PI^q_{PF}), are given in Table 4.6. Since reactive power output of generators were calculated considering their Q-limits ensuring that no violation of reactive power limits take place, some threshold value of PI^q_{PF} were selected to identify the critical contingencies. For the 14-bus system, it was taken as $1.0E-05$ for the PI obtained from the exact load flow method. The ranking list of contingencies captured based on the above threshold values is given in Table 4.6. The loading were changed by $\pm1.0\%, \pm3.0\%$ and $\pm5.0\%$ from their base values. It is observed from Table 4.6 that the list of severe contingencies, obtained from the performance indices based on optimal weights computed at base case and distribution factors, exactly matches with that obtained from the exact load flow method except for a load variation by +5.0%, in which an additional contingency L-7 gets listed and for −5.0%, in which contingencies G-4, L-5 & L-7 also get included. Thus, the optimal weights for PI^q_{DF} computed at base loading can be satisfactorily used even up to ±5.0% change in loading.

4.5.2 IEEE 30-bus System

For this system, 43 contingency cases have been simulated (38 line outages and 5 generator outages) considering single line or generator outage at a time. Load flow for outage of line (1-2) did not converge and hence, PI corresponding to this line outage have not been formed using the exact load flow method. Outage of lines (25-26), (9-6) and (7-4) have also not been considered because they result into islanding of the system causing the

Table 4.1: 14-bus system– Voltage performance indices using distribution factors

Outage case	PI^v_{DF} $(n=1)$	PI^v_{DF} $(n=2)$	PI^v_{DF} $(n=5)$	PI^v_{DF} $(n=10)$
$L-1$	$.3560E+00$	$.3493E-01$	$.2521E-03$	$.2600E-06$
$L-2$	$.4255E+00$	$.3755E-01$	$.1999E-03$	$.1317E-06$
$L-3$	$.3214E+00$	$.3069E-01$	$.1717E-03$	$.1132E-06$
$L-4$	$.1663E+01$	$.4141E+00$	$.5876E-01$	$.8236E-02$
$L-5$	$.5055E+00$	$.7412E-01$	$.1353E-02$	$.5668E-05$
$L-6$	$.3643E+00$	$.3400E-01$	$.2217E-03$	$.1937E-06$
$L-7$	$.3864E+00$	$.4965E-01$	$.7793E-03$	$.2803E-05$
$L-8$	$.1016E+01$	$.1888E+00$	$.1136E-01$	$.4226E-03$
$L-9$	$.1294E+01$	$.2905E+00$	$.2287E-01$	$.1322E-02$
$L-11$	$.7310E+00$	$.1316E+00$	$.5901E-02$	$.1321E-03$
$L-12$	$.3454E+00$	$.3274E-01$	$.1606E-03$	$.9305E-07$
$L-13$	$.3123E+00$	$.2647E-01$	$.1173E-03$	$.5410E-07$
$L-14$	$.3084E+00$	$.2801E-01$	$.1507E-03$	$.9390E-07$
$L-15$	$.3202E+00$	$.2777E-01$	$.1324E-03$	$.6967E-07$
$L-16$	$.3967E+00$	$.3769E-01$	$.1926E-03$	$.1171E-06$
$L-17$	$.4411E+00$	$.4894E-01$	$.3810E-03$	$.3987E-06$
$L-18$	$.3217E+00$	$.2729E-01$	$.1330E-03$	$.7199E-07$
$L-19$	$.3206E+00$	$.2676E-01$	$.1219E-03$	$.5928E-07$
$L-20$	$.3561E+00$	$.3265E-01$	$.1564E-03$	$.8655E-07$
$G-2$	$.1617E+01$	$.3692E+00$	$.4625E-01$	$.6614E-02$
$G-3$	$.5448E+01$	$.3161E+01$	$.3381E+01$	$.1431E+02$
$G-4$	$.1128E+01$	$.2247E+00$	$.1397E-01$	$.6413E-03$
$G-5$	$.2367E+01$	$.8968E+00$	$.7121E+00$	$.2312E+01$

Table 4.2: 14-bus system– Voltage performance indices using exact load flow

Outage case	PI^v_{PF} ($n=1$)	PI^v_{PF} ($n=2$)	PI^v_{PF} ($n=5$)	PI^v_{PF} ($n=10$)
$L-1$	$.4790E+00$	$.4084E-01$	$.2607E-03$	$.2992E-06$
$L-2$	$.4125E+00$	$.4748E-01$	$.4647E-03$	$.8148E-06$
$L-3$	$.3124E+00$	$.2799E-01$	$.1300E-03$	$.6363E-07$
$L-4$	$.5629E+00$	$.1131E+00$	$.4375E-02$	$.4893E-04$
$L-5$	$.4044E+00$	$.5173E-01$	$.6428E-03$	$.1274E-05$
$L-6$	$.2678E+00$	$.1543E-01$	$.2068E-04$	$.1475E-08$
$L-7$	$.4072E+00$	$.6547E-01$	$.2169E-02$	$.2296E-04$
$L-8$	$.4075E+01$	$.2187E+01$	$.3480E+01$	$.2847E+02$
$L-9$	$.1064E+01$	$.3218E+00$	$.4347E-01$	$.4630E-02$
$L-11$	$.4598E+00$	$.7557E-01$	$.2043E-02$	$.1694E-04$
$L-12$	$.8833E+00$	$.1399E+00$	$.4575E-02$	$.8585E-04$
$L-13$	$.4591E+00$	$.4102E-01$	$.1629E-03$	$.5811E-07$
$L-14$	$.3923E+00$	$.3586E-01$	$.2124E-03$	$.1841E-06$
$L-15$	$.4398E+00$	$.4014E-01$	$.1732E-03$	$.7686E-07$
$L-16$	$.1233E+01$	$.4734E+00$	$.1953E+00$	$.1578E+00$
$L-17$	$.9465E+00$	$.3731E+00$	$.2263E+00$	$.2558E+00$
$L-18$	$.3478E+00$	$.3000E-01$	$.1554E-03$	$.1002E-06$
$L-19$	$.3282E+00$	$.2715E-01$	$.1228E-03$	$.6010E-07$
$L-20$	$.4451E+00$	$.5677E-01$	$.6620E-03$	$.1341E-05$
$G-2$	$.4807E+00$	$.6543E-01$	$.1162E-02$	$.4811E-05$
$G-3$	$.2207E+01$	$.6879E+00$	$.1007E+00$	$.1473E-01$
$G-4$	$.4808E+00$	$.5834E-01$	$.7624E-03$	$.2351E-05$
$G-5$	$.1099E+01$	$.3520E+00$	$.1253E+00$	$.7692E-01$

Table 4.3: 14-bus system– Reactive power performance indices using distribution factors

Outage case	PI_{DF}^{q} $(n=1)$	PI_{DF}^{q} $(n=2)$	PI_{DF}^{q} $(n=5)$	PI_{DF}^{q} $(n=10)$
$L-1$	$.6998E+00$	$.1317E+00$	$.3997E-02$	$.4917E-04$
$L-2$	$.6808E+00$	$.1218E+00$	$.2792E-02$	$.1791E-04$
$L-3$	$.6794E+00$	$.1213E+00$	$.2761E-02$	$.1759E-04$
$L-4$	$.5783E+00$	$.9776E-01$	$.2322E-02$	$.1595E-04$
$L-5$	$.5998E+00$	$.9697E-01$	$.2022E-02$	$.1464E-04$
$L-6$	$.6480E+00$	$.1108E+00$	$.2366E-02$	$.1546E-04$
$L-7$	$.6603E+00$	$.1148E+00$	$.2502E-02$	$.1633E-04$
$L-8$	$.1117E+01$	$.4974E+00$	$.3607E+00$	$.6436E+00$
$L-9$	$.6631E+00$	$.1283E+00$	$.4627E-02$	$.5496E-04$
$L-11$	$.5677E+00$	$.8911E-01$	$.1919E-02$	$.1492E-04$
$L-12$	$.6805E+00$	$.1216E+00$	$.2768E-02$	$.1737E-04$
$L-13$	$.6881E+00$	$.1244E+00$	$.2904E-02$	$.1818E-04$
$L-14$	$.7836E+00$	$.1766E+00$	$.1184E-01$	$.5759E-03$
$L-15$	$.7982E+00$	$.1858E+00$	$.1434E-01$	$.8711E-03$
$L-16$	$.1071E+01$	$.4461E+00$	$.2730E+00$	$.3696E+00$
$L-17$	$.6868E+00$	$.1239E+00$	$.2880E-02$	$.1808E-04$
$L-18$	$.6872E+00$	$.1241E+00$	$.2890E-02$	$.1815E-04$
$L-19$	$.6881E+00$	$.1244E+00$	$.2904E-02$	$.1820E-04$
$L-20$	$.6859E+00$	$.1236E+00$	$.2867E-02$	$.1804E-04$
$G-2$	$.3390E+00$	$.6236E-01$	$.1772E-02$	$.1459E-04$
$G-3$	$.2966E+00$	$.4026E-01$	$.4373E-03$	$.7160E-06$
$G-4$	$.5488E+00$	$.9108E-01$	$.2128E-02$	$.1518E-04$
$G-5$	$.4548E+00$	$.8033E-01$	$.2063E-02$	$.1510E-04$

Table 4.4: 14-bus system– Reactive power performance indices using exact load flow

Outage case	PI_{PF}^{q} $(n=1)$	PI_{PF}^{q} $(n=2)$	PI_{PF}^{q} $(n=5)$	PI_{PF}^{q} $(n=10)$
$L-1$	$.5830E-01$	$.3137E-02$	$.1759E-05$	$.1547E-10$
$L-2$	$.2962E-01$	$.3195E-03$	$.3420E-08$	$.5759E-16$
$L-3$	$.3107E-02$	$.8910E-05$	$.7566E-12$	$.2862E-23$
$L-4$	$.2355E+00$	$.1548E-01$	$.2580E-04$	$.2471E-08$
$L-5$	$.4033E-01$	$.7765E-03$	$.4522E-07$	$.1022E-13$
$L-6$	$.1473E+00$	$.1828E-01$	$.1432E-03$	$.1025E-06$
$L-7$	$.1245E+00$	$.3917E-02$	$.5416E-06$	$.7892E-12$
$L-8$	$.1048E+01$	$.3532E+00$	$.1114E+00$	$.5804E-01$
$L-9$	$.6335E+00$	$.2646E+00$	$.1078E+00$	$.5808E-01$
$L-11$	$.7711E-01$	$.1867E-02$	$.1378E-06$	$.5869E-13$
$L-12$	$.9216E-01$	$.4316E-02$	$.1934E-05$	$.1607E-10$
$L-13$	$.7427E-01$	$.3422E-02$	$.1763E-05$	$.1547E-10$
$L-14$	$.3055E-01$	$.4697E-03$	$.8691E-08$	$.3512E-15$
$L-15$	$.2986E-03$	$.5555E-07$	$.2159E-17$	$.2331E-34$
$L-16$	$.3202E-01$	$.4572E-03$	$.5012E-08$	$.6304E-16$
$L-17$	$.7171E-01$	$.3350E-02$	$.1763E-05$	$.1550E-10$
$L-18$	$.4812E-02$	$.1137E-04$	$.7896E-12$	$.2902E-23$
$L-19$	$.3701E-04$	$.6970E-09$	$.2297E-22$	$.2437E-44$
$L-20$	$.1093E-01$	$.5856E-04$	$.4391E-10$	$.8621E-20$
$G-2$	$.2650E+00$	$.3650E-01$	$.6608E-03$	$.2179E-05$
$G-3$	$.2182E+00$	$.1775E-01$	$.4798E-04$	$.9421E-08$
$G-4$	$.7819E-01$	$.4052E-02$	$.3066E-05$	$.4699E-10$
$G-5$	$.8233E-01$	$.3511E-02$	$.1788E-05$	$.1591E-10$

Table 4.5: 14-bus system– Voltage ranking at different loading

Loading	Per. index	Relative ranking of contingencies	FR
Base case	PI_{PF}^{v}	$L-8, L-17, L-16, G-5, G-3, L-9$	—
	PI_{DF}^{v}	$L-8, L-17, L-16, G-5, G-3, L-9$	0.0
1.0% increase	PI_{PF}^{v}	$L-8, L-17, L-16, G-5, G-3, L-9$	—
	PI_{DF}^{v}	$G-3, L-8, L-17, G-5, L-9, L-16$	0.0
3.0% increase	PI_{PF}^{v}	$L-8, L-17, L-16, G-5, G-3, L-9$	—
	PI_{DF}^{v}	$G-3, L-17, L-8, G-5, L-9, L-11, L-16$	1/7
5.0% increase	PI_{PF}^{v}	$L-8, L-17, L-9, L-16, G-3, G-5$	—
	PI_{DF}^{v}	$G-3, L-17, L-8, G-4, L-11, L-16, L-5, L-20, L-3, L-1, L-14, L-6, L-18, L-15, L-19, L-12, L-7, L-13, L-9$	13/19
1.0% decrease	PI_{PF}^{v}	$L-8, L-16, L-17, G-5, G-3, L-9$	—
	PI_{DF}^{v}	$G-5, G-2, L-8, L-4, L-16, L-5, L-17, G-3, L-14, L-7, L-20, L-9$	6/12
3.0% decrease	PI_{PF}	$L-17, L-16, G-5, G-3, L-8, L-9$	—
	PI_{DF}^{v}	$G-5, G-2, L-4, L-8, L-5, G-3, L-16, L-7, L-14, L-20, L-11, G-4, L-17, L-9$	8/14
5.0% decrease	PI_{PF}^{v}	$L-17, L-16, G-5, G-3, L-8, L-9$	—
	PI_{DF}^{v}	$G-5, G-2, L-5, L-4, L-5, G-3, L-8, L-16, L-14, L-11, L-20, G-4, L-9, L-15, L-19, L-18, L-12, L-1, L-6, L-13, L-17$	15/21

Table 4.6: 14-bus system- Reactive power ranking at different loading

Loading	Per. index	Relative ranking of contingencies
Base case	PI^q_{PF}	$L-8, L-9, G-2, L-6, G-3, L-4$
	PI^q_{DF}	$L-8, L-9, G-2, L-6, G-3, L-4$
1.0% increase	PI^q_{PF}	$L-8, L-9, G-2, L-6, G-3, L-4$
	PI^q_{DF}	$L-8, L-9, G-2, L-6, L-4, G-3$
3.0% increase	PI^q_{PF}	$L-8, L-9, G-2, L-6, G-3, L-4$
	PI^q_{DF}	$L-8, L-9, G-2, L-6, L-4, G-3$
5.0% increase	PI^q_{PF}	$L-8, L-9, G-2, L-4, L-6, G-3$
	PI^q_{DF}	$L-8, L-9, G-2, L-4, L-6, L-7, G-3$
1.0% decrease	PI^q_{PF}	$L-8, L-9, G-2, L-6, L-4, G-3$
	PI^q_{DF}	$L-8, L-9, G-2, L-4, L-6, G-3$
3.0% decrease	PI^q_{PF}	$L-9, L-8, G-2, L-6, L-4, G-3$
	PI^q_{DF}	$L-8, L-9, G-2, L-4, G-3, L-6$
5.0% decrease	PI^q_{PF}	$L-9, L-8, L-6, G-2, L-4, L-1, G-3$
	PI^q_{DF}	$L-8, L-9, G-4, L-4, G-2, G-3, L-5, L-1, L-7, L-6$

Table 4.7: 14-bus system- Optimal weights for voltage performance indices

Bus no.	Weights	Bus no.	Weights	Bus no.	Weights
2	.18147987E+07	7	-.37965154E+07	12	.21729416E+08
3	-.79049287E+07	8	.17167704E+05	13	.13366819E+07
4	-.29772003E+03	9	-.97872402E+04	14	.19683013E+06
5	.18337014E+05	10	-.45752060E+08		
6	-.56466029E+08	11	.10406541E+07		

Table 4.8: 14-bus system- Optimal weights for reactive power performance indices

Bus no.	1	2	3	4	5
Weights	-.21091E06	.34179E06	-.56928E05	.10000E01	.15331E09

Jacobian to be singular.

The voltage and reactive power performance indices, with various exponents, computed by distribution factors method with unity weights are presented in Tables 4.9 and 4.10, respectively and those computed by exact load flow method are given in Tables 4.11 and 4.12, respectively. It is observed, from these tables, that some of the active and more severe contingencies (e.g. L-9, L-20 in Table 4.11) are ranked lower than the less severe contingencies (e.g. L-1, L-12, L-31 in Table 4.11). However, this masking effect are removed using exponent value of $n \geq 5$.

The ranking of contingencies based on performance indices computed with the distribution factors method (PI_{DF}) and the exact load flow method (PI_{PF}), even with higher order exponents, are different. In order to eliminate this misranking problem, the optimal weights associated with voltage and reactive power performance indices have been computed by solving equations (4.24) to (4.26). The ranking of voltage and reactive power performance indices were recomputed using these optimal weights which are presented in Tables 4.13 and 4.14, respectively. The values of optimal weights are given in Tables 4.15 and 4.16 for voltage and reactive power performance indices, respectively.

In order to establish the effectiveness of optimal weights, computed at base loading, for change in system loading conditions, the loading were first increased by 1.0%, 3.0% and 5.0% from their base values at all the buses simultaneously. The active contingencies, ranked by PI^v_{PF} based on exact load flow method, for these increased loading are presented in Table 4.13. The voltage ranking with distribution factors method using optimal weights (PI^v_{DF}) are presented in Table 4.13 for a capture rate of 1.0. The false-alarm rate for increase in loading by 1.0%, 3.0% and 5.0% were found to be 5/19, 8/22 and 12/27, respectively. For decrease in loading by 1.0%, the voltage ranking using distribution factors method provides a false alarm rate of 26/36 (Table 4.13) and hence, it was not tried for further decrease in loading. Thus, for IEEE 30-bus system the optimal weights for voltage PIs can be used up to +5.0% change in loading.

The optimal weights for reactive power performance indices, computed at base loading, were also used for different system loading conditions. The reactive power based ranking for change in loading by +1.0%, +3.0%, +5.0% and -1.0% from the base case have been given in Table 4.14. A threshold value of $1.0E-5$ was considered to select the critical contingencies computed from the exact load flow method. All the critical contingencies according to their reactive power severity using distribution factors method for different

loading are also presented in Table 4.14. From the Table 4.14, it is observed that only one non-critical contingency (G-3) is ranked as critical contingency for increase in loading by 1.0% and two non-critical contingencies (G-3 and L-4) are ranked as critical for load increase by 3.0% from their base value. However, the number of non-critical contingencies declared as critical contingencies increases to 9 for a load increase by +5%. With decrease in loading by 1.0% from the base case, the number of non-critical contingencies included in the list increases to 29 (out of total 38), which is unacceptable. Thus, the optimal weights associated with reactive power performance indices can be used for only increase in loading by +3.0%.

4.5.3 75-bus UPSEB System

75-bus UPSEB system consists of 15 generators each provided with unit transformers (L-1 to L-15). Since the outage of these transformers are same as the outage of generators, they have not been considered in the contingency list. The load flow did not converge for outage of lines L-110, L-111 & L-112 and generators G-5, G-12, G-14 & G-15, taken one at a time. The performance indices were, therefore, not formed (using exact load flow method) for these contingencies. However, these were considered to be the most severe contingency cases. Outage of lines L-103 to L-109, L-113 and L-114 caused the singularity of load flow Jacobian due to islanding of the system and hence, they were also not considered in the contingency list. Thus, total number of contingencies simulated for this system was 104.

The voltage and reactive power performance indices computed using distribution factors method and unity weights are given in Tables 4.17 & 4.18 and those computed by the exact load flow method have been presented in Tables 4.19 and 4.20, respectively. From these tables, it is observed that ranking of contingencies with lower exponent provide masking effect. This effect has been eliminated with higher exponents ($n \geq 5$).

The distribution factors based method provides misranking even with higher exponents. To eliminate this effect, the optimal weights were computed by solving equations (4.24) to (4.26). The ranking of voltage PI using optimal weights for base case and change in loading by ±1.0% and ±2.0% have been presented in Table 4.21.

Table 4.10: 30-bus system– Reactive power performance indices using distribution factors

Outage case	PI_{DF}^q $(n=1)$	PI_{DF}^q $(n=2)$	PI_{DF}^q $(n=5)$	PI_{DF}^q $(n=10)$
$L-1$	$.1636E+01$	$.6581E+00$	$.1833E+00$	$.6641E-01$
$L-2$	$.1641E+01$	$.6589E+00$	$.1835E+00$	$.6648E-01$
$L-3$	$.1634E+01$	$.6582E+00$	$.1836E+00$	$.6662E-01$
$L-4$	$.1645E+01$	$.6592E+00$	$.1835E+00$	$.6648E-01$
$L-5$	$.1897E+01$	$.9600E+00$	$.5563E+00$	$.6969E+00$
$L-6$	$.1698E+01$	$.7397E+00$	$.2848E+00$	$.2168E+00$
$L-7$	$.1643E+01$	$.6606E+00$	$.1851E+00$	$.6803E-01$
$L-8$	$.1983E+01$	$.1056E+01$	$.9166E+00$	$.3024E+01$
$L-9$	$.1643E+01$	$.6620E+00$	$.1860E+00$	$.6841E-01$
$L-10$	$.1627E+01$	$.6590E+00$	$.1835E+00$	$.6649E-01$
$L-11$	$.2637E+01$	$.2692E+01$	$.2539E+02$	$.3203E+04$
$L-12$	$.1627E+01$	$.6811E+00$	$.2093E+00$	$.9530E-01$
$L-13$	$.1646E+01$	$.6594E+00$	$.1835E+00$	$.6649E-01$
$L-14$	$.1719E+01$	$.7567E+00$	$.3127E+00$	$.2783E+00$
$L-15$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-16$	$.1646E+01$	$.6594E+00$	$.1835E+00$	$.6650E-01$
$L-17$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6650E-01$
$L-18$	$.1649E+01$	$.6597E+00$	$.1835E+00$	$.6649E-01$
$L-19$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6650E-01$
$L-20$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-21$	$.1649E+01$	$.6597E+00$	$.1835E+00$	$.6649E-01$
$L-22$	$.1649E+01$	$.6597E+00$	$.1835E+00$	$.6649E-01$
$L-23$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-24$	$.1649E+01$	$.6597E+00$	$.1835E+00$	$.6649E-01$
$L-25$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-26$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-27$	$.1649E+01$	$.6597E+00$	$.1835E+00$	$.6649E-01$
$L-28$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-29$	$.1649E+01$	$.6597E+00$	$.1835E+00$	$.6649E-01$
$L-30$	$.1649E+01$	$.6597E+00$	$.1835E+00$	$.6649E-01$
$L-31$	$.1649E+01$	$.6597E+00$	$.1835E+00$	$.6649E-01$
$L-32$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-33$	$.1640E+01$	$.6597E+00$	$.1845E+00$	$.6751E-01$
$L-34$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-35$	$.1647E+01$	$.6595E+00$	$.1835E+00$	$.6649E-01$
$L-36$	$.1648E+01$	$.6596E+00$	$.1835E+00$	$.6649E-01$
$L-37$	$.1617E+01$	$.6580E+00$	$.1835E+00$	$.6648E-01$
$L-38$	$.1644E+01$	$.6592E+00$	$.1835E+00$	$.6649E-01$
$G-2$	$.1109E+01$	$.4054E+00$	$.8269E-01$	$.1615E-01$
$G-3$	$.1580E+01$	$.6587E+00$	$.1862E+00$	$.6948E-01$
$G-4$	$.1178E+01$	$.4770E+00$	$.1398E+00$	$.5696E-01$

Table 4.11: 30-bus system– Voltage performance indices using exact load flow

Outage case	PI^v_{PF} $(n=1)$	PI^v_{PF} $(n=2)$	PI^v_{PF} $(n=5)$	PI^v_{PF} $(n=10)$
$L-1$	$.6775E+01$	$.2810E+01$	$.1120E+01$	$.1002E+01$
$L-2$	$.5223E+01$	$.1660E+01$	$.2893E+00$	$.6688E-01$
$L-3$	$.1250E+02$	$.9306E+01$	$.2271E+02$	$.4104E+03$
$L-4$	$.5930E+01$	$.1934E+01$	$.3977E+00$	$.1713E+00$
$L-5$	$.1780E+02$	$.1991E+02$	$.4708E+03$	$.6303E+06$
$L-6$	$.4950E+01$	$.1528E+01$	$.2728E+00$	$.8905E-01$
$L-7$	$.4564E+01$	$.1354E+01$	$.2181E+00$	$.5566E-01$
$L-8$	$.4364E+01$	$.1294E+01$	$.3785E+00$	$.4834E+00$
$L-9$	$.5484E+01$	$.4176E+01$	$.6722E+02$	$.2256E+05$
$L-10$	$.4045E+01$	$.1036E+01$	$.1167E+00$	$.2141E-01$
$L-12$	$.7189E+01$	$.3071E+01$	$.1361E+01$	$.1580E+01$
$L-13$	$.1147E+02$	$.8927E+01$	$.2533E+02$	$.5139E+03$
$L-14$	$.4776E+01$	$.1418E+01$	$.2234E+00$	$.5752E-01$
$L-15$	$.4744E+01$	$.1384E+01$	$.1976E+00$	$.3716E-01$
$L-16$	$.7290E+01$	$.3670E+01$	$.3239E+01$	$.1120E+02$
$L-17$	$.5274E+01$	$.1755E+01$	$.3529E+00$	$.1136E+00$
$L-18$	$.4058E+01$	$.1050E+01$	$.1195E+00$	$.2160E-01$
$L-19$	$.4317E+01$	$.1210E+01$	$.1503E+00$	$.2594E-01$
$L-20$	$.5475E+01$	$.2581E+01$	$.2994E+01$	$.1852E+02$
$L-21$	$.4305E+01$	$.1343E+01$	$.3707E+00$	$.2603E+00$
$L-22$	$.4679E+01$	$.1764E+01$	$.1452E+01$	$.7116E+01$
$L-23$	$.6126E+01$	$.3723E+01$	$.1111E+02$	$.2724E+03$
$L-24$	$.4322E+01$	$.1252E+01$	$.2874E+00$	$.1963E+00$
$L-25$	$.4779E+01$	$.1516E+01$	$.3380E+00$	$.1601E+00$
$L-26$	$.4156E+01$	$.1088E+01$	$.1220E+00$	$.2132E-01$
$L-27$	$.3978E+01$	$.1040E+01$	$.1260E+00$	$.2227E-01$
$L-28$	$.4381E+01$	$.1227E+01$	$.1610E+00$	$.2986E-01$
$L-29$	$.4088E+01$	$.1081E+01$	$.1254E+00$	$.2161E-01$
$L-30$	$.4011E+01$	$.1019E+01$	$.1135E+00$	$.2088E-01$
$L-31$	$.7440E+01$	$.3028E+01$	$.1552E+01$	$.4460E+01$
$L-32$	$.1129E+02$	$.9131E+01$	$.7809E+02$	$.2069E+05$
$L-33$	$.5695E+01$	$.2082E+01$	$.6393E+00$	$.4812E+00$
$L-34$	$.4618E+01$	$.1222E+01$	$.1409E+00$	$.2409E-01$
$L-35$	$.4630E+01$	$.1329E+01$	$.2511E+00$	$.1085E+00$
$L-36$	$.4142E+01$	$.1037E+01$	$.1153E+00$	$.2125E-01$
$L-37$	$.4052E+01$	$.1043E+01$	$.1199E+00$	$.2264E-01$
$L-38$	$.3981E+01$	$.1013E+01$	$.1191E+00$	$.2537E-01$
$G-2$	$.5344E+01$	$.1744E+01$	$.4810E+00$	$.4812E+00$
$G-3$	$.1149E+02$	$.6872E+01$	$.8621E+01$	$.5695E+02$
$G-4$	$.8815E+01$	$.4735E+01$	$.7384E+01$	$.1627E+03$
$G-5$	$.5904E+01$	$.2428E+01$	$.3112E+01$	$.4228E+02$
$G-6$	$.1022E+02$	$.5627E+01$	$.4976E+01$	$.1887E+02$

Table 4.12: 30-bus system- Reactive power performance indices using exact load flow

Outage case	PI^q_{PF} $(n=1)$	PI^q_{PF} $(n=2)$	PI^q_{PF} $(n=5)$	PI^q_{PF} $(n=10)$
$L-1$	$.3753E-01$	$.6565E-03$	$.2243E-07$	$.2441E-14$
$L-2$	$.6779E-02$	$.2246E-04$	$.2732E-11$	$.1930E-22$
$L-3$	$.1375E+00$	$.9676E-02$	$.1640E-04$	$.1238E-08$
$L-4$	$.2860E-01$	$.7242E-03$	$.4498E-07$	$.1012E-13$
$L-5$	$.3893E+00$	$.1071E+00$	$.1137E-01$	$.6468E-03$
$L-6$	$.2109E+00$	$.3083E-01$	$.5047E-03$	$.1273E-05$
$L-7$	$.7806E-01$	$.4093E-02$	$.3222E-05$	$.5189E-10$
$L-8$	$.2598E-01$	$.3775E-03$	$.6634E-08$	$.2177E-15$
$L-9$	$.1741E-01$	$.1052E-03$	$.1167E-09$	$.5472E-19$
$L-10$	$.1400E-02$	$.1906E-05$	$.1605E-13$	$.1288E-26$
$L-12$	$.3779E+00$	$.1071E+00$	$.1142E-01$	$.6519E-03$
$L-13$	$.2039E+00$	$.2346E-01$	$.2097E-03$	$.2184E-06$
$L-14$	$.1204E+00$	$.6773E-02$	$.8641E-05$	$.3700E-09$
$L-15$	$.6503E-03$	$.1409E-06$	$.4866E-17$	$.4603E-34$
$L-16$	$.2606E-01$	$.2982E-03$	$.2673E-08$	$.3367E-16$
$L-17$	$.2650E-01$	$.3955E-03$	$.8379E-08$	$.3506E-15$
$L-18$	$.3807E-04$	$.7208E-09$	$.3213E-22$	$.5118E-44$
$L-19$	$.1150E-01$	$.6917E-04$	$.8925E-10$	$.3919E-19$
$L-20$	$.9862E-02$	$.4520E-04$	$.2306E-10$	$.2416E-20$
$L-21$	$.3594E-02$	$.6600E-05$	$.2289E-12$	$.2533E-24$
$L-22$	$.6420E-02$	$.2732E-04$	$.1090E-10$	$.5932E-21$
$L-23$	$.1311E-01$	$.1202E-03$	$.4585E-09$	$.1051E-17$
$L-24$	$.1539E-01$	$.1445E-03$	$.6633E-09$	$.2192E-17$
$L-25$	$.9044E-03$	$.3749E-06$	$.1814E-15$	$.1627E-30$
$L-26$	$.5787E-04$	$.1489E-08$	$.1668E-21$	$.1362E-42$
$L-27$	$.2723E-03$	$.4129E-07$	$.7573E-18$	$.2802E-35$
$L-28$	$.2194E-02$	$.2232E-05$	$.1574E-13$	$.1223E-26$
$L-29$	$.1039E-02$	$.5599E-06$	$.5044E-15$	$.1243E-29$
$L-30$	$.3742E-04$	$.1093E-08$	$.1220E-21$	$.7439E-43$
$L-31$	$.2332E-01$	$.2147E-03$	$.7382E-09$	$.1705E-17$
$L-32$	$.4248E-01$	$.8841E-03$	$.4533E-07$	$.9850E-14$
$L-33$	$.3791E+00$	$.1070E+00$	$.1137E-01$	$.6468E-03$
$L-34$	$.2170E-03$	$.3172E-07$	$.5397E-18$	$.1456E-35$
$L-35$	$.3815E-03$	$.9802E-07$	$.9061E-17$	$.4105E-33$
$L-36$	$.2601E-04$	$.4561E-09$	$.1339E-22$	$.8963E-45$
$L-37$	$.1305E-01$	$.1694E-03$	$.1195E-08$	$.7134E-17$
$L-38$	$.7868E-03$	$.4268E-06$	$.3549E-15$	$.6298E-30$
$G-2$	$.2810E+00$	$.4920E-01$	$.1551E-02$	$.1202E-04$
$G-3$	$.7170E-01$	$.2487E-02$	$.6821E-06$	$.2287E-11$
$G-4$	$.1721E+00$	$.1714E-01$	$.8884E-04$	$.3887E-07$
$G-5$	$.2778E+00$	$.6500E-01$	$.3419E-02$	$.5846E-04$
$G-6$	$.1115E+00$	$.1092E-01$	$.3970E-04$	$.7882E-08$

Table 4.13: 30-bus system– Voltage ranking at different loading

Loading	method	Ranking of contingencies	FR
Base	PI^v_{PF}	$L-11, L-5, L-32, L-9, L-13, L-3, L-23, G-3, G-4, G-6$	—
Base	PI^v_{DF}	$L-11, L-5, L-32, L-9, L-13, L-3, L-23, G-3, G-4, G-6$	0.0
1.0% increase	PI^v_{PF}	$L-11, L-5, L-9, L-32, L-3, L-13, G-3, L-23, G-4, G-6, L-16, L-12, G-5, L-33$	—
	PI^v_{DF}	$G-6, G-3, G-2, G-5, L-12, L-5, L-11, L-3, L-31, L-14, L-32, L-13, L-2, L-9, L-16, L-23, G-4, L-35, L-33$	5/19
3.0% increase	PI^v_{PF}	$L-11, L-5, L-9, L-32, L-3, L-13, G-3, L-12, L-23, L-33, G-4, G-6, G-5, L-16$	—
	PI^v_{DF}	$G-6, G-3, G-2, G-5, L-12, L-11, L-5, L-3, L-14, L-31, L-6, L-32, L-13, L-2, L-33, L-16, G-4, L-7, L-17, L-25, L-9, L-23$	8/22
5.0% increase	PI^v_{PF}	$L-11, L-5, L-9, L-3, L-32, L-12, G-3, L-13, L-33, G-4, L-23, G-6, G-5, L-16, L-20$	—
	PI^v_{DF}	$G-6, G-3, G-2, G-5, L-12, L-11, L-5, L-3, L-6, L-14, L-31, L-32, L-2, L-13, L-33, L-35, L-16, L-1, L-17, L-25, L-8, G-4, L-28, L-9, L-23, L-38, L-20$	12/27
1.0% decrease	PI_{PF}	$L-11, L-5, L-32, L-9, L-13, L-3, L-23, G-3, G-4, G-6$	—
	PI^v_{DF}	$G-4, L-9, L-23, L-38, L-20, L-22, L-27, L-28, L-13, L-25, L-16, L-35, L-17, L-7, L-21, L-8, L-18, G-3, L-30, L-36, L-10, L-2, L-33, L-26, G-6, L-29, L-32, L-19, L-1, L-14, L-3, L-24, L-15, l-31, L-11, L-5, L-32, L-9, L-13, L-23, L-3, G-4, G-6$	26/36

Table 4.14: 30-bus system- Reactive power ranking at different loading

Loading	method	Ranking of contingencies
Base case	PI^q_{PF}	$L-11, L-12, L-5, L-33, G-5, G-2, L-6, L-13, G-6, L-3$
	PI^q_{DF}	$L-11, L-12, L-5, L-33, G-5, G-2, L-6, L-13, G-6, L-3$
1.0% increase	PI^q_{PF}	$L-11, L-5, L-12, L-33, G-5, G-2, L-6, L-13, G-6, L-3$
	PI^q_{DF}	$G-6, L-11, L-3, L-12, G-5, G-2, L-13, L-5, G-3, L-6, L-33$
3.0% increase	PI^q_{PF}	$L-11, G-5, G-2, L-5, L-12, L-33, L-6, G-6, L-13, L-3, L-7, L-14$
	PI^q_{DF}	$G-6, L-11, L-3, L-12, G-5, G-2, G-3, L-5, L-14, L-6, L-33, L-4, L-7, L-13$
5.0% increase	PI^q_{PF}	$L-11, L-13, L-5, G-3, L-6, L-3, L-12, L-33, G-6, G-5, L-7, L-14$
	PI^q_{DF}	$L-5, L-12, L-33, G-6, L-6, G-3, L-13, G-5, L-3, L-14, L-7, G-4, L-9, L-32, L-4, L-17, L-16, L-37, L-1, L-10, L-11$
1.0% decrease	PI^q_{PF}	$L-11, L-5, L-12, L-33, G-5, G-2, L-6, L-13, G-6$
	PI^q_{DF}	$G-6, L-11, L-3, L-12, L-14, L-31, L-32, L-24, L-29, L-30, L-19, L-27, L-17, L-23, L-18, L-22, L-21, L-36, L-28, L-26, L-15, L-20, L-34, L-25, L-35, L-33, L-16, L-4, L-10, L-38, L-9, L-37, L-6, L-13, L-7, L-2, L-5, G-2, G-5$

Table 4.15: 30-bus system- Optimal weights for voltage performance indices

Bus no.	Weights	Bus no.	Weights	Bus no.	Weights
2	.39587408E+07	12	.31421841E+02	22	-.97998108E+04
3	.13647064E+07	13	.10083638E+04	23	-.31450612E+04
4	.43562338E+05	14	-.71895837E+05	24	.23879150E+05
5	.11537955E+05	15	-.49405308E+04	25	.22688716E+07
6	-.25655518E+06	16	.62492749E+05	26	-.24624721E+05
7	-.26946415E+07	17	-.26170761E+05	27	-.11265073E+04
8	.62166275E+05	18	-.17472415E+03	28	-.17734082E+04
9	.63883514E+07	19	.38497480E+03	29	-.24218477E+07
10	-.28440639E+04	20	-.37170105E+03	30	.24789934E+06
11	-.15136768E+03	21	.31570436E+04	–	–

Table 4.16: 30-bus system- Optimal weights for reactive power performance indices

Bus no.	1	2	3	4	5	6
Weights	.58725E06	.19623E02	.23527E02	.90903E05	-.15851E02	-.14695E07

The optimal weights calculated at base operating point have been used for computing the PIs for the change in loading conditions. The weights associated with voltage PIs have been given in Table 4.22. It is observed from Table 4.21, that increase in loading by 1.0% and 2.0% results into the false alarm rate of 22/49 and 29/63, respectively. However decrease in loading by 1.0% and 2.0% gives the false alarm rate of 10/24 and 17/25 for a capture rate of 1.0. Thus, the optimal weights associated with the voltage PIs can be used for only ±1.0% change in loading.

The optimization problem (4.24) to (4.26) gave infeasible solution for calculation of optimal weight associated with reactive power performance index (PI^q). This may be due to the inaccuracy in computation of reactive power output of sources using the distribution factors. For this system, in order to obtain feasible solution, some contingency constraints (e.g. for L-38, L-74, L-75, L-78, L-91, G-2, G-5, G-8, G-13) defined by equations (4.25) and (4.26) have been relaxed in calculation of optimal weights. The ranking of contingencies obtained with the optimal weights in base case and for change in loading by ±2.0% are given in Table 4.23. A threshold value of 1.0E+02 have been considered to select critical contingencies. The optimal weights for reactive power PI are presented in Table 4.24. It is observed from Table 4.23 that in order to capture all the critical contingencies based on the above threshold value of PI, almost all non-critical contingencies have to be included in the ranking list, even for the base case condition. Hence, the reactive power performance index based method can not be effectively used for contingency ranking in this system.

4.6 Conclusions

In this Chapter, voltage as well as reactive power performance indices have been suggested for contingency ranking. A simple approach to find out optimal weights of the performance indices have been proposed. The study results on the three systems reveal that

(i) The use of higher order exponent for both voltage and reactive power performance indices eliminates the masking effect. The exponent of 5 or more is recommended to overcome the masking problem.

(ii) The performance indices computed by the distribution factors method using optimal weights minimizes the misranking effects.

Table 4.17: 75-bus system- Voltage performance indices using distribution factors

Outage case	PI^v_{DF} $(n=1)$	PI^v_{DF} $(n=2)$	PI^v_{DF} $(n=5)$	PI^v_{DF} $(n=10)$
$L-16$	$.3066E+02$	$.2712E+02$	$.2347E+03$	$.8905E+05$
$L-17$	$.3066E+02$	$.2712E+02$	$.2347E+03$	$.8905E+05$
$L-18$	$.2743E+02$	$.2195E+02$	$.1593E+03$	$.5704E+05$
$L-19$	$.2700E+02$	$.2007E+02$	$.1073E+03$	$.2679E+05$
$L-20$	$.2700E+02$	$.2007E+02$	$.1073E+03$	$.2679E+05$
$L-21$	$.2608E+02$	$.2077E+02$	$.1419E+03$	$.4541E+05$
$L-22$	$.2608E+02$	$.2077E+02$	$.1419E+03$	$.4541E+05$
$L-23$	$.2624E+02$	$.2001E+02$	$.1188E+03$	$.3204E+05$
$L-24$	$.2624E+02$	$.2001E+02$	$.1188E+03$	$.3204E+05$
$L-25$	$.2460E+02$	$.1685E+02$	$.7957E+02$	$.1630E+05$
$L-26$	$.2460E+02$	$.1685E+02$	$.7957E+02$	$.1630E+05$
$L-27$	$.2460E+02$	$.1685E+02$	$.7957E+02$	$.1630E+05$
$L-28$	$.3179E+02$	$.2870E+02$	$.3905E+03$	$.4676E+06$
$L-29$	$.3179E+02$	$.2870E+02$	$.3905E+03$	$.4676E+06$
$L-30$	$.3012E+02$	$.2406E+02$	$.1593E+03$	$.5541E+05$
$L-31$	$.3292E+02$	$.2745E+02$	$.1750E+03$	$.5692E+05$
$L-32$	$.3292E+02$	$.2745E+02$	$.1750E+03$	$.5692E+05$
$L-33$	$.2849E+02$	$.2618E+02$	$.3365E+03$	$.2590E+06$
$L-34$	$.2849E+02$	$.2618E+02$	$.3365E+03$	$.2590E+06$
$L-35$	$.2230E+02$	$.1745E+02$	$.1260E+03$	$.3906E+05$
$L-36$	$.2230E+02$	$.1745E+02$	$.1260E+03$	$.3906E+05$
$L-37$	$.2230E+02$	$.1745E+02$	$.1260E+03$	$.3906E+05$
$L-38$	$.1935E+02$	$.1605E+02$	$.1586E+03$	$.7134E+05$
$L-39$	$.2422E+02$	$.1713E+02$	$.6799E+02$	$.3612E+04$
$L-40$	$.1558E+02$	$.8930E+01$	$.2789E+02$	$.2178E+04$
$L-41$	$.2165E+02$	$.1688E+02$	$.1243E+03$	$.3911E+05$
$L-42$	$.2518E+02$	$.1904E+02$	$.1162E+03$	$.3239E+05$
$L-43$	$.2854E+02$	$.2403E+02$	$.1774E+03$	$.6069E+05$
$L-44$	$.1887E+02$	$.1157E+02$	$.4673E+02$	$.6408E+04$
$L-45$	$.1887E+02$	$.1157E+02$	$.4673E+02$	$.6408E+04$
$L-46$	$.2883E+02$	$.2265E+02$	$.1404E+03$	$.4357E+05$
$L-47$	$.2159E+02$	$.1401E+02$	$.5883E+02$	$.9421E+04$
$L-48$	$.3033E+02$	$.2463E+02$	$.1694E+03$	$.6179E+05$
$L-49$	$.2775E+02$	$.2090E+02$	$.1211E+03$	$.3416E+05$
$L-50$	$.2678E+02$	$.1963E+02$	$.1071E+03$	$.2755E+05$
$L-51$	$.2721E+02$	$.2025E+02$	$.1104E+03$	$.2870E+05$
$L-52$	$.2923E+02$	$.2289E+02$	$.1452E+03$	$.4720E+05$

Table ... Contd.

Table 4.17 (Contd.) ...

Outage case	PI^v_{DF} $(n=1)$	PI^v_{DF} $(n=2)$	PI^v_{DF} $(n=5)$	PI^v_{DF} $(n=10)$
$L-53$	$.3016E+02$	$.2424E+02$	$.1626E+03$	$.5750E+05$
$L-54$	$.2791E+02$	$.2104E+02$	$.1226E+03$	$.3501E+05$
$L-55$	$.3019E+02$	$.2429E+02$	$.1629E+03$	$.5762E+05$
$L-56$	$.3039E+02$	$.2459E+02$	$.1671E+03$	$.6025E+05$
$L-57$	$.2505E+02$	$.1745E+02$	$.8102E+02$	$.1647E+05$
$L-58$	$.2753E+02$	$.2056E+02$	$.1178E+03$	$.3259E+05$
$L-59$	$.2892E+02$	$.2284E+02$	$.1447E+03$	$.4586E+05$
$L-60$	$.2971E+02$	$.2384E+02$	$.1594E+03$	$.5541E+05$
$L-61$	$.2815E+02$	$.2144E+02$	$.1272E+03$	$.3736E+05$
$L-62$	$.2674E+02$	$.1933E+02$	$.1032E+03$	$.2587E+05$
$L-63$	$.2674E+02$	$.1933E+02$	$.1032E+03$	$.2587E+05$
$L-64$	$.2143E+02$	$.2132E+02$	$.4328E+03$	$.6449E+06$
$L-65$	$.2908E+02$	$.2474E+02$	$.2329E+03$	$.1386E+06$
$L-66$	$.2187E+02$	$.1973E+02$	$.2222E+03$	$.1221E+06$
$L-67$	$.3214E+02$	$.2718E+02$	$.2029E+03$	$.8308E+05$
$L-68$	$.3144E+02$	$.2962E+02$	$.3361E+03$	$.1452E+06$
$L-69$	$.1944E+02$	$.1147E+02$	$.2895E+02$	$.1233E+04$
$L-70$	$.1838E+02$	$.1049E+02$	$.2675E+02$	$.1576E+04$
$L-71$	$.2783E+02$	$.2169E+02$	$.1116E+03$	$.9388E+04$
$L-72$	$.3108E+02$	$.2762E+02$	$.2576E+03$	$.1053E+06$
$L-73$	$.3129E+02$	$.3182E+02$	$.5914E+03$	$.7262E+06$
$L-74$	$.1095E+02$	$.3598E+01$	$.4492E+01$	$.8252E+02$
$L-75$	$.1283E+02$	$.5186E+01$	$.9012E+01$	$.2983E+03$
$L-76$	$.2748E+02$	$.2183E+02$	$.1478E+03$	$.4993E+05$
$L-77$	$.2872E+02$	$.2219E+02$	$.1361E+03$	$.4208E+05$
$L-78$	$.2924E+02$	$.2401E+02$	$.1805E+03$	$.7275E+05$
$L-79$	$.2253E+02$	$.1506E+02$	$.5134E+02$	$.2101E+04$
$L-80$	$.2975E+02$	$.2425E+02$	$.1717E+03$	$.6417E+05$
$L-81$	$.3070E+02$	$.2536E+02$	$.1825E+03$	$.7069E+05$
$L-82$	$.3049E+02$	$.2523E+02$	$.1806E+03$	$.6839E+05$
$L-83$	$.2740E+02$	$.2203E+02$	$.1483E+03$	$.4674E+05$
$L-84$	$.2795E+02$	$.2249E+02$	$.1539E+03$	$.5101E+05$
$L-85$	$.3089E+02$	$.2564E+02$	$.1856E+03$	$.7226E+05$
$L-86$	$.2671E+02$	$.1944E+02$	$.1012E+03$	$.2460E+05$
$L-87$	$.2660E+02$	$.1941E+02$	$.1051E+03$	$.2668E+05$
$L-88$	$.1947E+02$	$.1194E+02$	$.4430E+02$	$.5389E+04$
$L-89$	$.1947E+02$	$.1194E+02$	$.4430E+02$	$.5389E+04$
$L-90$	$.1485E+02$	$.6655E+01$	$.6564E+01$	$.3845E+02$

Table ... Contd.

Table 4.17 (Contd.) ...

Outage case	PI_{DF}^{v} $(n=1)$	PI_{DF}^{v} $(n=2)$	PI_{DF}^{v} $(n=5)$	PI_{DF}^{v} $(n=10)$
$L-91$	$.1533E+02$	$.7312E+01$	$.1753E+02$	$.1043E+04$
$L-92$	$.3086E+02$	$.2529E+02$	$.1774E+03$	$.6704E+05$
$L-93$	$.2394E+02$	$.1651E+02$	$.7763E+02$	$.1540E+05$
$L-94$	$.2394E+02$	$.1651E+02$	$.7763E+02$	$.1540E+05$
$L-95$	$.2801E+02$	$.2118E+02$	$.1244E+03$	$.3592E+05$
$L-96$	$.2801E+02$	$.2118E+02$	$.1244E+03$	$.3592E+05$
$L-97$	$.3107E+02$	$.2556E+02$	$.1811E+03$	$.6949E+05$
$L-98$	$.3034E+02$	$.2594E+02$	$.2083E+03$	$.8328E+05$
$L-99$	$.3034E+02$	$.2594E+02$	$.2083E+03$	$.8328E+05$
$L-100$	$.2991E+02$	$.2389E+02$	$.1581E+03$	$.5474E+05$
$L-101$	$.2665E+02$	$.2031E+02$	$.1190E+03$	$.3166E+05$
$L-102$	$.3196E+02$	$.2727E+02$	$.2186E+03$	$.1017E+06$
$L-110$	$.1357E+02$	$.5661E+01$	$.5317E+01$	$.3953E+02$
$L-111$	$.1544E+02$	$.7490E+01$	$.9438E+01$	$.7532E+02$
$L-112$	$.1292E+02$	$.6010E+01$	$.1479E+02$	$.8141E+03$
$G-2$	$.1893E+02$	$.1461E+02$	$.1249E+03$	$.4487E+05$
$G-3$	$.2401E+02$	$.1574E+02$	$.4973E+02$	$.1990E+04$
$G-4$	$.1166E+02$	$.4550E+01$	$.3195E+01$	$.1185E+02$
$G-5$	$.1991E+02$	$.1131E+02$	$.2215E+02$	$.4035E+03$
$G-6$	$.1318E+02$	$.6048E+01$	$.1316E+02$	$.6319E+03$
$G-7$	$.1500E+02$	$.8570E+01$	$.3390E+02$	$.3779E+04$
$G-8$	$.1527E+02$	$.8783E+01$	$.3697E+02$	$.2733E+04$
$G-9$	$.2350E+02$	$.1882E+02$	$.1534E+03$	$.6059E+05$
$G-10$	$.1568E+02$	$.9286E+01$	$.3711E+02$	$.4471E+04$
$G-11$	$.3015E+02$	$.5305E+02$	$.4213E+04$	$.3661E+08$
$G-12$	$.2087E+02$	$.1797E+02$	$.1773E+03$	$.8123E+05$
$G-13$	$.2257E+02$	$.1872E+02$	$.1663E+03$	$.7029E+05$
$G-14$	$.2141E+02$	$.1415E+02$	$.4356E+02$	$.1751E+04$
$G-15$	$.6511E+02$	$.1243E+03$	$.1392E+05$	$.5304E+09$

Table 4.18: 75-bus system– Reactive power performance indices using distribution factors

Outage case	PI^q_{DF} $(n=1)$	PI^q_{DF} $(n=2)$	PI^q_{DF} $(n=5)$	PI^q_{DF} $(n=10)$
$L-16$	$.3246E+01$	$.1317E+01$	$.4353E+00$	$.2036E+00$
$L-17$	$.3246E+01$	$.1317E+01$	$.4353E+00$	$.2036E+00$
$L-18$	$.3235E+01$	$.1316E+01$	$.4349E+00$	$.2033E+00$
$L-19$	$.3385E+01$	$.1339E+01$	$.4350E+00$	$.2031E+00$
$L-20$	$.3385E+01$	$.1339E+01$	$.4350E+00$	$.2031E+00$
$L-21$	$.3312E+01$	$.1321E+01$	$.4339E+00$	$.2023E+00$
$L-22$	$.3312E+01$	$.1321E+01$	$.4339E+00$	$.2023E+00$
$L-23$	$.3270E+01$	$.1317E+01$	$.4344E+00$	$.2027E+00$
$L-24$	$.3270E+01$	$.1317E+01$	$.4344E+00$	$.2027E+00$
$L-25$	$.3664E+01$	$.1501E+01$	$.4817E+00$	$.2138E+00$
$L-26$	$.3664E+01$	$.1501E+01$	$.4817E+00$	$.2138E+00$
$L-27$	$.3664E+01$	$.1501E+01$	$.4817E+00$	$.2138E+00$
$L-28$	$.3274E+01$	$.1318E+01$	$.4355E+00$	$.2038E+00$
$L-29$	$.3274E+01$	$.1318E+01$	$.4355E+00$	$.2038E+00$
$L-30$	$.3234E+01$	$.1317E+01$	$.4354E+00$	$.2037E+00$
$L-31$	$.3236E+01$	$.1316E+01$	$.4351E+00$	$.2034E+00$
$L-32$	$.3236E+01$	$.1316E+01$	$.4351E+00$	$.2034E+00$
$L-33$	$.3241E+01$	$.1317E+01$	$.4353E+00$	$.2037E+00$
$L-34$	$.3241E+01$	$.1317E+01$	$.4353E+00$	$.2037E+00$
$L-35$	$.3325E+01$	$.1324E+01$	$.4343E+00$	$.2026E+00$
$L-36$	$.3325E+01$	$.1324E+01$	$.4343E+00$	$.2026E+00$
$L-37$	$.3325E+01$	$.1324E+01$	$.4343E+00$	$.2026E+00$
$L-38$	$.4442E+01$	$.2803E+01$	$.9275E+01$	$.3921E+03$
$L-39$	$.7251E+01$	$.1765E+02$	$.3464E+04$	$.5997E+08$
$L-40$	$.5751E+01$	$.7671E+01$	$.3268E+03$	$.5325E+06$
$L-41$	$.3348E+01$	$.1329E+01$	$.4345E+00$	$.2028E+00$
$L-42$	$.3329E+01$	$.1325E+01$	$.4353E+00$	$.2036E+00$
$L-43$	$.3238E+01$	$.1316E+01$	$.4353E+00$	$.2037E+00$
$L-44$	$.4498E+01$	$.2915E+01$	$.1080E+02$	$.5373E+03$
$L-45$	$.4498E+01$	$.2915E+01$	$.1080E+02$	$.5373E+03$
$L-46$	$.3259E+01$	$.1317E+01$	$.4354E+00$	$.2037E+00$
$L-47$	$.4134E+01$	$.2127E+01$	$.2331E+01$	$.1818E+02$
$L-48$	$.3237E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-49$	$.3314E+01$	$.1323E+01$	$.4354E+00$	$.2038E+00$
$L-50$	$.3387E+01$	$.1340E+01$	$.4356E+00$	$.2037E+00$
$L-51$	$.3371E+01$	$.1335E+01$	$.4355E+00$	$.2037E+00$
$L-52$	$.3245E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$

Table . . . Contd.

Table 4.18 (Contd.) ...

Outage case	PI^q_{DF} $(n = 1)$	PI^q_{DF} $(n = 2)$	PI^q_{DF} $(n = 5)$	PI^q_{DF} $(n = 10)$
$L-53$	$.3235E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-54$	$.3304E+01$	$.1321E+01$	$.4354E+00$	$.2038E+00$
$L-55$	$.3235E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-56$	$.3235E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-57$	$.3653E+01$	$.1492E+01$	$.4764E+00$	$.2120E+00$
$L-58$	$.3328E+01$	$.1325E+01$	$.4354E+00$	$.2037E+00$
$L-59$	$.3245E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-60$	$.3235E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-61$	$.3286E+01$	$.1319E+01$	$.4354E+00$	$.2038E+00$
$L-62$	$.3413E+01$	$.1348E+01$	$.4360E+00$	$.2037E+00$
$L-63$	$.3413E+01$	$.1348E+01$	$.4360E+00$	$.2037E+00$
$L-64$	$.3401E+01$	$.1340E+01$	$.4304E+00$	$.1985E+00$
$L-65$	$.3247E+01$	$.1317E+01$	$.4354E+00$	$.2038E+00$
$L-66$	$.3322E+01$	$.1323E+01$	$.4341E+00$	$.2025E+00$
$L-67$	$.3714E+01$	$.1547E+01$	$.5170E+00$	$.2370E+00$
$L-68$	$.3247E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-69$	$.6069E+01$	$.9470E+01$	$.6118E+03$	$.1869E+07$
$L-70$	$.5734E+01$	$.7695E+01$	$.3327E+03$	$.5520E+06$
$L-71$	$.8317E+01$	$.2753E+02$	$.1130E+05$	$.6385E+09$
$L-72$	$.3251E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-73$	$.3240E+01$	$.1317E+01$	$.4354E+00$	$.2038E+00$
$L-74$	$.1282E+02$	$.9328E+02$	$.2596E+06$	$.3369E+12$
$L-75$	$.9921E+01$	$.4610E+02$	$.4295E+05$	$.9224E+10$
$L-76$	$.3240E+01$	$.1317E+01$	$.4353E+00$	$.2037E+00$
$L-77$	$.3262E+01$	$.1317E+01$	$.4354E+00$	$.2038E+00$
$L-78$	$.3265E+01$	$.1318E+01$	$.4354E+00$	$.2038E+00$
$L-79$	$.7136E+01$	$.1669E+02$	$.2975E+04$	$.4425E+08$
$L-80$	$.3239E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-81$	$.3248E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-82$	$.3242E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-83$	$.3258E+01$	$.1317E+01$	$.4354E+00$	$.2037E+00$
$L-84$	$.3243E+01$	$.1317E+01$	$.4354E+00$	$.2037E+00$
$L-85$	$.3251E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-86$	$.3440E+01$	$.1359E+01$	$.4365E+00$	$.2037E+00$
$L-87$	$.3399E+01$	$.1343E+01$	$.4358E+00$	$.2037E+00$
$L-88$	$.4759E+01$	$.3644E+01$	$.2692E+02$	$.3507E+04$
$L-89$	$.4759E+01$	$.3644E+01$	$.2692E+02$	$.3507E+04$
$L-90$	$.1790E+02$	$.2169E+03$	$.2184E+07$	$.2384E+14$

Table ... Contd.

Table 4.18 (Contd.) ...

Outage case	PI^q_{DF} $(n=1)$	PI^q_{DF} $(n=2)$	PI^q_{DF} $(n=5)$	PI^q_{DF} $(n=10)$
$L-91$	$.7372E+01$	$.1846E+02$	$.3898E+04$	$.7594E+08$
$L-92$	$.3242E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-93$	$.3707E+01$	$.1540E+01$	$.5112E+00$	$.2324E+00$
$L-94$	$.3707E+01$	$.1540E+01$	$.5112E+00$	$.2324E+00$
$L-95$	$.3298E+01$	$.1321E+01$	$.4354E+00$	$.2037E+00$
$L-96$	$.3298E+01$	$.1321E+01$	$.4354E+00$	$.2037E+00$
$L-97$	$.3246E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-98$	$.3249E+01$	$.1317E+01$	$.4354E+00$	$.2038E+00$
$L-99$	$.3249E+01$	$.1317E+01$	$.4354E+00$	$.2038E+00$
$L-100$	$.3235E+01$	$.1317E+01$	$.4355E+00$	$.2038E+00$
$L-101$	$.3329E+01$	$.1325E+01$	$.4353E+00$	$.2037E+00$
$L-102$	$.3398E+01$	$.1343E+01$	$.4359E+00$	$.2038E+00$
$L-110$	$.1410E+02$	$.1200E+03$	$.4910E+06$	$.1205E+13$
$L-111$	$.2143E+02$	$.3330E+03$	$.6412E+07$	$.2055E+15$
$L-112$	$.7191E+01$	$.1707E+02$	$.3157E+04$	$.4982E+08$
$G-2$	$.3170E+01$	$.1256E+01$	$.3849E+00$	$.1647E+00$
$G-3$	$.6120E+01$	$.1192E+02$	$.1216E+04$	$.7392E+07$
$G-4$	$.1653E+02$	$.1916E+03$	$.1604E+07$	$.1287E+14$
$G-5$	$.1557E+02$	$.1614E+03$	$.1040E+07$	$.5409E+13$
$G-6$	$.6808E+01$	$.1515E+02$	$.2290E+04$	$.2620E+08$
$G-7$	$.4806E+01$	$.3820E+01$	$.3227E+02$	$.5068E+04$
$G-8$	$.1340E+02$	$.1149E+03$	$.4426E+06$	$.9797E+12$
$G-9$	$.5825E+01$	$.8091E+01$	$.3832E+03$	$.7327E+06$
$G-10$	$.4349E+01$	$.2813E+01$	$.9423E+01$	$.4044E+03$
$G-11$	$.3394E+01$	$.1355E+01$	$.4329E+00$	$.2000E+00$
$G-12$	$.7588E+02$	$.5316E+04$	$.6591E+10$	$.2172E+21$
$G-13$	$.1238E+02$	$.8512E+02$	$.2058E+06$	$.2117E+12$
$G-14$	$.2608E+02$	$.5253E+03$	$.2011E+08$	$.2022E+16$
$G-15$	$.3686E+01$	$.2035E+01$	$.3640E+01$	$.5619E+02$

Table 4.19: 75-bus system– Voltage performance indices using exact load flow

Outage case	PI_{PF}^{v} $(n=1)$	PI_{PF}^{v} $(n=2)$	PI_{PF}^{v} $(n=5)$	PI_{PF}^{v} $(n=10)$
$L-16$	$.6364E+01$	$.1599E+01$	$.3239E+00$	$.1321E+00$
$L-17$	$.6364E+01$	$.1599E+01$	$.3239E+00$	$.1321E+00$
$L-18$	$.5339E+01$	$.1140E+01$	$.1737E+00$	$.5925E-01$
$L-19$	$.5278E+01$	$.1065E+01$	$.1415E+00$	$.3574E-01$
$L-20$	$.5278E+01$	$.1065E+01$	$.1415E+00$	$.3574E-01$
$L-21$	$.5984E+01$	$.1368E+01$	$.2821E+00$	$.1732E+00$
$L-22$	$.5984E+01$	$.1368E+01$	$.2821E+00$	$.1732E+00$
$L-23$	$.5370E+01$	$.1084E+01$	$.1250E+00$	$.2618E-01$
$L-24$	$.5370E+01$	$.1084E+01$	$.1250E+00$	$.2618E-01$
$L-25$	$.4882E+01$	$.1032E+01$	$.1492E+00$	$.4029E-01$
$L-26$	$.4882E+01$	$.1032E+01$	$.1492E+00$	$.4029E-01$
$L-27$	$.4882E+01$	$.1032E+01$	$.1492E+00$	$.4029E-01$
$L-28$	$.6895E+01$	$.2699E+01$	$.7049E+01$	$.2297E+03$
$L-29$	$.6895E+01$	$.2699E+01$	$.7049E+01$	$.2297E+03$
$L-30$	$.5738E+01$	$.1317E+01$	$.2787E+00$	$.1567E+00$
$L-31$	$.4897E+01$	$.8742E+00$	$.7960E-01$	$.1628E-01$
$L-32$	$.4897E+01$	$.8742E+00$	$.7960E-01$	$.1628E-01$
$L-33$	$.6546E+01$	$.1896E+01$	$.8504E+00$	$.1303E+01$
$L-34$	$.6546E+01$	$.1896E+01$	$.8504E+00$	$.1303E+01$
$L-35$	$.5798E+01$	$.1304E+01$	$.2297E+00$	$.1055E+00$
$L-36$	$.5798E+01$	$.1304E+01$	$.2297E+00$	$.1055E+00$
$L-37$	$.5798E+01$	$.1304E+01$	$.2297E+00$	$.1055E+00$
$L-38$	$.8028E+01$	$.3272E+01$	$.7483E+01$	$.2499E+03$
$L-39$	$.9181E+01$	$.3296E+01$	$.2685E+01$	$.2113E+02$
$L-40$	$.1075E+02$	$.4921E+01$	$.8387E+01$	$.1301E+03$
$L-41$	$.5866E+01$	$.1394E+01$	$.3504E+00$	$.3719E+00$
$L-42$	$.5410E+01$	$.1144E+01$	$.1692E+00$	$.5051E-01$
$L-43$	$.6520E+01$	$.1590E+01$	$.3696E+00$	$.2599E+00$
$L-44$	$.4950E+01$	$.9802E+00$	$.1359E+00$	$.5205E-01$
$L-45$	$.4950E+01$	$.9802E+00$	$.1359E+00$	$.5205E-01$
$L-46$	$.5376E+01$	$.1179E+01$	$.2165E+00$	$.9625E-01$
$L-47$	$.5083E+01$	$.9855E+00$	$.1233E+00$	$.3854E-01$
$L-48$	$.5561E+01$	$.1224E+01$	$.2144E+00$	$.9291E-01$
$L-49$	$.5332E+01$	$.1186E+01$	$.2314E+00$	$.1143E+00$
$L-50$	$.5586E+01$	$.1211E+01$	$.1747E+00$	$.5279E-01$
$L-51$	$.5693E+01$	$.1178E+01$	$.1727E+00$	$.5416E-01$
$L-52$	$.5197E+01$	$.1146E+01$	$.2070E+00$	$.8713E-01$

Table ... Contd.

Table 4.19 (Contd.) ...

Outage case	PI^v_{PF} $(n=1)$	PI^v_{PF} $(n=2)$	PI^v_{PF} $(n=5)$	PI^v_{PF} $(n=10)$
$L-53$	$.5505E+01$	$.1218E+01$	$.2254E+00$	$.1068E+00$
$L-54$	$.5256E+01$	$.1153E+01$	$.2072E+00$	$.8745E-01$
$L-55$	$.5547E+01$	$.1228E+01$	$.2259E+00$	$.1071E+00$
$L-56$	$.5509E+01$	$.1216E+01$	$.2266E+00$	$.1089E+00$
$L-57$	$.5239E+01$	$.1121E+01$	$.1578E+00$	$.4202E-01$
$L-58$	$.5070E+01$	$.1088E+01$	$.1929E+00$	$.7417E-01$
$L-59$	$.5191E+01$	$.1035E+01$	$.1152E+00$	$.2363E-01$
$L-60$	$.5881E+01$	$.1437E+01$	$.4463E+00$	$.5605E+00$
$L-61$	$.5166E+01$	$.1123E+01$	$.1903E+00$	$.7051E-01$
$L-62$	$.5131E+01$	$.1119E+01$	$.1984E+00$	$.7915E-01$
$L-63$	$.5131E+01$	$.1119E+01$	$.1984E+00$	$.7915E-01$
$L-64$	$.8841E+01$	$.4698E+01$	$.2676E+02$	$.3288E+04$
$L-65$	$.5723E+01$	$.1280E+01$	$.2351E+00$	$.1059E+00$
$L-66$	$.5909E+01$	$.1368E+01$	$.2796E+00$	$.1856E+00$
$L-67$	$.5393E+01$	$.1168E+01$	$.2179E+00$	$.1266E+00$
$L-68$	$.8221E+01$	$.5613E+01$	$.5341E+02$	$.9360E+04$
$L-69$	$.6545E+01$	$.1761E+01$	$.8212E+00$	$.2482E+01$
$L-70$	$.6697E+01$	$.1846E+01$	$.9026E+00$	$.2975E+01$
$L-71$	$.1352E+02$	$.7045E+01$	$.1475E+02$	$.5310E+03$
$L-72$	$.6051E+01$	$.1689E+01$	$.9041E+00$	$.2405E+01$
$L-73$	$.7623E+01$	$.4472E+01$	$.4562E+02$	$.1012E+05$
$L-74$	$.4342E+01$	$.8927E+00$	$.1411E+00$	$.5361E-01$
$L-75$	$.4831E+01$	$.9967E+00$	$.1526E+00$	$.5853E-01$
$L-76$	$.5614E+01$	$.1203E+01$	$.1884E+00$	$.6358E-01$
$L-77$	$.5155E+01$	$.1135E+01$	$.1967E+00$	$.7610E-01$
$L-78$	$.1060E+02$	$.4664E+01$	$.7461E+01$	$.1886E+03$
$L-79$	$.8001E+01$	$.2537E+01$	$.1658E+01$	$.9110E+01$
$L-80$	$.7283E+01$	$.2083E+01$	$.9790E+00$	$.3341E+01$
$L-81$	$.5854E+01$	$.1322E+01$	$.2753E+00$	$.1706E+00$
$L-82$	$.6191E+01$	$.1469E+01$	$.2687E+00$	$.9451E-01$
$L-83$	$.5741E+01$	$.1253E+01$	$.2047E+00$	$.7458E-01$
$L-84$	$.5653E+01$	$.1240E+01$	$.2116E+00$	$.8314E-01$
$L-85$	$.5732E+01$	$.1273E+01$	$.2395E+00$	$.1248E+00$
$L-86$	$.4984E+01$	$.1052E+01$	$.1865E+00$	$.6770E-01$
$L-87$	$.5215E+01$	$.1124E+01$	$.1824E+00$	$.6301E-01$
$L-88$	$.5066E+01$	$.1046E+01$	$.1531E+00$	$.4711E-01$
$L-89$	$.5066E+01$	$.1046E+01$	$.1531E+00$	$.4711E-01$
$L-90$	$.9359E+01$	$.5724E+01$	$.3716E+02$	$.3428E+04$

Table ... Contd.

Table 4.19 (Contd.) ...

Outage case	PI_{PF}^{v} $(n=1)$	PI_{PF}^{v} $(n=2)$	PI_{PF}^{v} $(n=5)$	PI_{PF}^{v} $(n=10)$
$L-91$	$.4688E+01$	$.9747E+00$	$.1541E+00$	$.5073E-01$
$L-92$	$.5580E+01$	$.1236E+01$	$.2278E+00$	$.1091E+00$
$L-93$	$.5299E+01$	$.1072E+01$	$.1351E+00$	$.3255E-01$
$L-94$	$.5299E+01$	$.1072E+01$	$.1351E+00$	$.3255E-01$
$L-95$	$.5309E+01$	$.1155E+01$	$.2101E+00$	$.9138E-01$
$L-96$	$.5309E+01$	$.1155E+01$	$.2101E+00$	$.9138E-01$
$L-97$	$.4654E+01$	$.1006E+01$	$.1604E+00$	$.4685E-01$
$L-98$	$.5767E+01$	$.1301E+01$	$.2443E+00$	$.1165E+00$
$L-99$	$.5767E+01$	$.1301E+01$	$.2443E+00$	$.1165E+00$
$L-100$	$.5462E+01$	$.1206E+01$	$.2200E+00$	$.1004E+00$
$L-101$	$.5160E+01$	$.1020E+01$	$.1123E+00$	$.2420E-01$
$L-102$	$.5318E+01$	$.1127E+01$	$.1643E+00$	$.4805E-01$
$G-2$	$.6788E+01$	$.1934E+01$	$.7307E+00$	$.1225E+01$
$G-3$	$.9714E+01$	$.3679E+01$	$.2395E+01$	$.8748E+01$
$G-4$	$.5899E+01$	$.1385E+01$	$.3922E+00$	$.4386E+00$
$G-6$	$.5223E+01$	$.1185E+01$	$.3432E+00$	$.4290E+00$
$G-7$	$.4938E+01$	$.1022E+01$	$.1799E+00$	$.8902E-01$
$G-8$	$.1387E+02$	$.3339E+02$	$.9908E+04$	$.4439E+09$
$G-9$	$.5881E+01$	$.1368E+01$	$.3206E+00$	$.2546E+00$
$G-10$	$.5542E+01$	$.1164E+01$	$.2062E+00$	$.1254E+00$
$G-11$	$.1389E+02$	$.1379E+02$	$.2079E+03$	$.1072E+06$
$G-13$	$.7497E+01$	$.2537E+01$	$.2504E+01$	$.2545E+02$

Table 4.20: 75-bus system– Reactive power performance indices using exact load flow

Outage case	PI^q_{PF} $(n=1)$	PI^q_{PF} $(n=2)$	PI^q_{PF} $(n=5)$	PI^q_{PF} $(n=10)$
$L-16$	$.1059E+00$	$.9303E-02$	$.2642E-04$	$.3490E-08$
$L-17$	$.1059E+00$	$.9303E-02$	$.2642E-04$	$.3490E-08$
$L-18$	$.2038E+00$	$.9315E-02$	$.1693E-04$	$.1428E-08$
$L-19$	$.2234E+00$	$.1669E-01$	$.8472E-04$	$.3579E-07$
$L-20$	$.2234E+00$	$.1669E-01$	$.8472E-04$	$.3579E-07$
$L-21$	$.4413E+00$	$.5900E-01$	$.1442E-02$	$.1010E-04$
$L-22$	$.4413E+00$	$.5900E-01$	$.1442E-02$	$.1010E-04$
$L-23$	$.2066E+00$	$.1004E-01$	$.8519E-05$	$.1826E-09$
$L-24$	$.2066E+00$	$.1004E-01$	$.8519E-05$	$.1826E-09$
$L-25$	$.1972E+00$	$.7159E-02$	$.2083E-05$	$.1009E-10$
$L-26$	$.1972E+00$	$.7159E-02$	$.2083E-05$	$.1009E-10$
$L-27$	$.1972E+00$	$.7159E-02$	$.2083E-05$	$.1009E-10$
$L-28$	$.2471E-01$	$.5054E-03$	$.1828E-07$	$.1671E-14$
$L-29$	$.2471E-01$	$.5054E-03$	$.1828E-07$	$.1671E-14$
$L-30$	$.3797E+00$	$.9223E-01$	$.7547E-02$	$.2847E-03$
$L-31$	$.2417E-01$	$.1782E-03$	$.5042E-09$	$.1019E-17$
$L-32$	$.2417E-01$	$.1782E-03$	$.5042E-09$	$.1019E-17$
$L-33$	$.5106E-01$	$.9945E-03$	$.8427E-07$	$.3549E-13$
$L-34$	$.5106E-01$	$.9945E-03$	$.8427E-07$	$.3549E-13$
$L-35$	$.2156E+00$	$.1322E-01$	$.3599E-04$	$.6331E-08$
$L-36$	$.2156E+00$	$.1322E-01$	$.3599E-04$	$.6331E-08$
$L-37$	$.2156E+00$	$.1322E-01$	$.3599E-04$	$.6331E-08$
$L-38$	$.2212E+01$	$.7396E+00$	$.2946E+00$	$.2154E+00$
$L-39$	$.6377E+01$	$.9955E+01$	$.6522E+03$	$.2115E+07$
$L-40$	$.6925E+01$	$.7847E+01$	$.1445E+03$	$.9434E+05$
$L-41$	$.4109E+00$	$.7212E-01$	$.4083E-02$	$.8333E-04$
$L-42$	$.7844E-01$	$.1318E-02$	$.7807E-07$	$.2651E-13$
$L-43$	$.1060E+00$	$.3214E-02$	$.5706E-06$	$.8906E-12$
$L-44$	$.4628E+00$	$.3180E-01$	$.1292E-03$	$.7506E-07$
$L-45$	$.4628E+00$	$.3180E-01$	$.1292E-03$	$.7506E-07$
$L-46$	$.2559E-01$	$.1408E-03$	$.1978E-09$	$.1346E-18$
$L-47$	$.2310E+00$	$.7890E-02$	$.4469E-05$	$.9335E-10$
$L-48$	$.4922E-02$	$.1432E-04$	$.2389E-11$	$.2854E-22$
$L-49$	$.4601E-01$	$.5310E-03$	$.5903E-08$	$.1416E-15$
$L-50$	$.6926E-01$	$.1982E-02$	$.2033E-06$	$.1164E-12$
$L-51$	$.6939E+00$	$.1878E+00$	$.3275E-01$	$.5307E-02$
$L-52$	$.1550E+00$	$.1054E-01$	$.1831E-04$	$.1467E-08$

Table ... Contd.

Table 4.20 (Contd.) ...

Outage case	PI^q_{PF} $(n=1)$	PI^q_{PF} $(n=2)$	PI^q_{PF} $(n=5)$	PI^q_{PF} $(n=10)$
$L-53$	$.9929E-02$	$.3205E-04$	$.8468E-11$	$.3198E-21$
$L-54$	$.8026E-01$	$.2299E-02$	$.3893E-06$	$.6716E-12$
$L-55$	$.4931E-02$	$.6012E-05$	$.1020E-12$	$.4730E-25$
$L-56$	$.1072E-01$	$.4027E-04$	$.2027E-10$	$.2016E-20$
$L-57$	$.2009E+00$	$.1206E-01$	$.3203E-04$	$.5073E-08$
$L-58$	$.2172E+00$	$.1290E-01$	$.1454E-04$	$.5162E-09$
$L-59$	$.2529E-01$	$.1002E-03$	$.5273E-10$	$.7007E-20$
$L-60$	$.5125E-02$	$.2084E-04$	$.6245E-11$	$.1950E-21$
$L-61$	$.7371E-01$	$.2480E-02$	$.7934E-06$	$.3140E-11$
$L-62$	$.1363E+00$	$.5716E-02$	$.3151E-05$	$.4443E-10$
$L-63$	$.1363E+00$	$.5716E-02$	$.3151E-05$	$.4443E-10$
$L-64$	$.2376E+01$	$.2214E+01$	$.1982E+02$	$.1962E+04$
$L-65$	$.1861E-01$	$.1594E-03$	$.9019E-09$	$.4066E-17$
$L-66$	$.7026E+00$	$.1818E+00$	$.3755E-01$	$.7047E-02$
$L-67$	$.1429E+01$	$.1731E+01$	$.1258E+02$	$.7907E+03$
$L-68$	$.4461E-01$	$.1639E-02$	$.3434E-06$	$.5895E-12$
$L-69$	$.4094E+01$	$.4751E+01$	$.9202E+02$	$.4092E+05$
$L-70$	$.4170E+01$	$.5025E+01$	$.1089E+03$	$.5767E+05$
$L-71$	$.1148E+02$	$.4886E+02$	$.4628E+05$	$.1071E+11$
$L-72$	$.8952E-02$	$.6955E-04$	$.1284E-09$	$.8241E-19$
$L-73$	$.4916E-01$	$.2021E-02$	$.5811E-06$	$.1689E-11$
$L-74$	$.2054E+01$	$.8252E+00$	$.3441E+00$	$.3011E+00$
$L-75$	$.1224E+01$	$.2547E+00$	$.1519E-01$	$.5027E-03$
$L-76$	$.1036E+00$	$.2994E-02$	$.5319E-06$	$.1035E-11$
$L-77$	$.5021E-01$	$.4591E-03$	$.1981E-08$	$.7263E-17$
$L-78$	$.1423E+02$	$.1140E+03$	$.4273E+06$	$.9129E+12$
$L-79$	$.6428E+01$	$.1344E+02$	$.1652E+04$	$.1362E+08$
$L-80$	$.3414E+01$	$.4012E+01$	$.6339E+02$	$.1948E+05$
$L-81$	$.3276E-01$	$.6293E-03$	$.2541E-07$	$.3212E-14$
$L-82$	$.1473E+00$	$.5345E-02$	$.3358E-05$	$.5409E-10$
$L-83$	$.5817E-01$	$.6304E-03$	$.1193E-07$	$.6436E-15$
$L-84$	$.2263E-01$	$.1027E-03$	$.1414E-09$	$.9225E-19$
$L-85$	$.1192E-01$	$.1377E-03$	$.7121E-09$	$.2536E-17$
$L-86$	$.4042E+00$	$.5273E-01$	$.7641E-03$	$.2327E-05$
$L-87$	$.5466E-01$	$.5390E-03$	$.3550E-08$	$.4118E-16$
$L-88$	$.4077E+00$	$.2688E-01$	$.6418E-04$	$.1009E-07$
$L-89$	$.4077E+00$	$.2688E-01$	$.6418E-04$	$.1009E-07$
$L-90$	$.4985E+01$	$.5437E+01$	$.1037E+03$	$.5243E+05$

Table ... Contd.

Table 4.20 (Contd.) ...

Outage case	PI^q_{PF} $(n=1)$	PI^q_{PF} $(n=2)$	PI^q_{PF} $(n=5)$	PI^q_{PF} $(n=10)$
$L-91$	$.8760E+00$	$.1428E+00$	$.4191E-02$	$.4597E-04$
$L-92$	$.2451E-02$	$.1130E-05$	$.6077E-15$	$.6913E-30$
$L-93$	$.1044E+00$	$.1661E-02$	$.4788E-07$	$.4802E-14$
$L-94$	$.1044E+00$	$.1661E-02$	$.4788E-07$	$.4802E-14$
$L-95$	$.6031E-01$	$.1230E-02$	$.8765E-07$	$.3636E-13$
$L-96$	$.6031E-01$	$.1230E-02$	$.8765E-07$	$.3636E-13$
$L-97$	$.1035E+01$	$.4706E+00$	$.3745E+00$	$.6982E+00$
$L-98$	$.5591E-02$	$.1118E-04$	$.6406E-12$	$.1771E-23$
$L-99$	$.5591E-02$	$.1118E-04$	$.6406E-12$	$.1771E-23$
$L-100$	$.8064E-02$	$.1234E-04$	$.2401E-12$	$.1083E-24$
$L-101$	$.3511E-01$	$.1555E-03$	$.7914E-10$	$.9840E-20$
$L-102$	$.3374E+00$	$.7215E-01$	$.4214E-02$	$.8876E-04$
$G-2$	$.3980E+01$	$.1325E+02$	$.2040E+04$	$.2081E+08$
$G-3$	$.5867E+01$	$.1439E+02$	$.2103E+04$	$.2209E+08$
$G-4$	$.3791E+01$	$.2549E+01$	$.5680E+01$	$.7833E+02$
$G-6$	$.3070E+01$	$.1906E+01$	$.5018E+01$	$.1074E+03$
$G-7$	$.6888E+00$	$.9238E-01$	$.3052E-02$	$.4443E-04$
$G-8$	$.4125E+01$	$.2685E+01$	$.5277E+01$	$.5883E+02$
$G-9$	$.6408E+01$	$.3859E+02$	$.2959E+05$	$.4377E+10$
$G-10$	$.7038E+00$	$.1904E+00$	$.4312E-01$	$.9293E-02$
$G-11$	$.2107E+01$	$.2522E+01$	$.3093E+02$	$.4785E+04$
$G-13$	$.3816E+02$	$.1318E+04$	$.2014E+09$	$.2029E+18$

Table 4.21: 75-bus system- Voltage ranking at different loading

Loading	method	Ranking of contingencies	FR
Base case	PI^v_{PF}	$L-110, L-111, L-112, G-5, G-12, G-14, G-15, G-8, G-11, L-68, L-73, L-90, L-64, L-71, L-40, L-38, L-78, L-28, L-29, L-39, G-13, G-3$	—
	PI^v_{DF}	$L-110, L-111, L-112, G-5, G-12, G-14, G-15, G-8, G-11, L-68, L-73, L-90, L-64, L-71, L-40, L-38, L-78, L-28, L-29, L-39, G-13, G-3$	0.0
1.0% increase	PI^v_{PF}	$L-40, L-71, L-78, L-79, L-110, L-111, L-112, G-5, G-8, G-12, G-13, G-14, G-15, G-11, L-90, L-68, L-73, L-64, L-38, G-3, L-39, L-28, L-29, L-70, L-69, L-80, G-4$	—
	PI^v_{DF}	$L-110, L-111, L-112, G-5, G-12, G-14, G-15, L-90, G-8, G-4, L-40, L-38, G-10, L-64, G-7, L-36, L-37, L-35, L-41, L-66, G-13, G-11, L-76, L-46, L-52, L-77, L-49, L-55, L-100, L-53, L-95, L-61, L-80, L-54, G-3, L-78, L-69, L-39, L-42, L-68, L-51, L-70, L-28, L-29, L-71, L-23, L-24, L-73, L-79$	22/49
2.0% increase	PI^v_{PF}	$L-38, L-39, L-40, L-69, L-70, L-71, L-78, L-79, L-90, L-110, L-111, L-112, G-3, G-4, G-5, G-6, G-8, G-11, G-12, G-13, G-14, G-15, L-64, L-68, L-73, L-28, L-29, L-80, G-2, L-33, L-34, G-9, G-10, L-72, L-41, G-7$	—
	PI_{DF}	$L-110, L-111, L-112, G-5, G-12, G-14, G-15, L-90, G-8, L-36, L-37, L-35, L-41, L-38, L-40, G-10, L-57, G-7, L-86, L-58, L-87, L-62, L-63, L-21, L-22, L-25, L-26, L-27, L-51, G-13, L-93, L-94, L-95, L-96, L-69, L-54, L-46, G-11, L-47, L-42, L-76, G-9L-64, L-80, G-6, G-4, L-49, L-56, L-48, L-79, L-78, G-3, L-68, L-73, G-2, L-71, L-39, L-70, L-28, L-29, L-23, L-24, L-33, L-34, L-72$	29/63
1.0% decrease	PI^v_{PF}	$L-110, G-12, G-15, G-8, G-11, L-68, L-73, L-64, L-90, L-28, L-29, L-38, L-71, L-111$	—
	PI^v_{DF}	$G-15, L-71, L-79, L-39, G-3, G-8, G-4, L-69, L-11, L-110, G-11, L-38, L-40, G-2, G-12, L-64, G-7, L-66, L-31, L-73, L-68, L-90, L-28, L-29$	10/24
2.0% decrease	PI^v_{PF}	$G-12, G-15, G-8, G-11, L-68, L-73, L-64, L-90$	—
	PI^v_{DF}	$G-12, G-15, L-90, L-71, L-79, G-14, L-39, G-3, L-111, G-8, G-4, L-110, L-68, G-5, L-38, L-40, G-11, G-4, L-70, G-10, L-64, G-7, L-73, L-$	17/25

Table 4.22: 75-bus system– Optimal weights for voltage performance indices

Bus no.	Weights	Bus no.	Weights	Bus no.	Weights
2	-.37258E+03	27	-.45588E+03	52	-.26237E+04
3	0.63817E+02	28	0.12871E+03	53	0.10107E+03
4	0.41091E+03	29	0.30359E+04	54	0.73722E+03
5	0.12456E+04	30	-.11948E+04	55	-.10621E+05
6	0.13138E+04	31	-.14786E+04	56	-.85094E+03
7	0.17072E+04	32	0.28256E+04	57	0.25366E+04
8	0.87260E+03	33	-.74802E+03	58	0.21961E+04
9	0.11886E+01	34	0.35279E+04	59	0.34142E+04
10	0.27053E+02	35	-.41239E+03	60	0.45189E+03
11	0.70764E+03	36	0.48189E+03	61	-.32781E+03
12	0.15428E+01	37	-.44265E+02	62	-.33963E+04
13	0.13961E+01	38	0.11748E+03	63	-.23961E+04
14	-.67597E+03	39	-.26367E+04	64	0.42233E+04
15	-.10471E+04	40	0.15400E+02	65	0.12229E+03
16	0.12559E+03	41	-.15874E+05	66	-.22656E+05
17	0.11540E+03	42	-.61199E+04	67	-.64078E+01
18	0.59971E+02	43	-.28825E+04	68	0.95620E+00
19	-.80742E+02	44	-.50649E+04	69	0.69709E+01
20	-.15293E+04	45	0.31865E+04	70	-.59899E+03
21	-.64941E+02	46	-.36549E+04	71	-.59452E+03
22	0.48357E+04	47	-.15336E+01	72	0.79184E+03
23	-.10349E+03	48	0.35564E+02	73	-.13027E+04
24	-.53031E+01	49	0.25847E+01	74	-.12374E+03
25	0.23812E+04	50	0.32855E+04	75	0.48906E+04
26	0.13760E+03	51	0.53422E+03	–	———

Table 4.23: 75-bus system– Reactive power ranking at different loading

Loading	method	Ranking of contingencies
Base case	PI^q_{PF}	$L-110, L-111, L-112, G-5, G-12, G-14, G-15, G-13, L-78, L-71, G-9, G-3, G-2, L-79, L-39, L-40, L-70, L-90$
	PI^q_{DF}	$L-110, L-111, L-112, G-5, G-12, G14, G-15, G-8, G-2, G-5, L-74, L-75, L-71, L-91, L-38, L-79, L-41, L-39, L-40, L-70, L-90, L-69, G-13, L-93, L-94, G-11, L-23, L-24, L-64, L-21, L-22, L-25, L-26, L-27, G-9$
2.0% increase	PI^q_{PF}	$L-38, L-39, L-40, L-69, L-70, L-71, L-78, L-79, L-90, L-110, L-111, L-112, G-3, G-4, G-5, G-8, G-11, G-12, G-13, G-14, G-15, G-9, G-6, G-2, L-80, L-64, L-67$
	PI^q_{DF}	$L-110, L-111, L-112, G-5, G-12, G-14, G-15, L-90, G-8, G-5, G-2, G-10, L-71, L-38, G-13, L-40, G-11, L-39, L-64, L-23, L-24, L-41, L-35, L-36, L-37, L-79, L-69, L-21, L-22, G-9, L-70, L-66, L-43$
2.0% decrease	PI^q_{PF}	$G-12, G-15, G-13, G-9, L-71, G-2, L-78, L-110, L-90$
	PI^q_{DF}	$L-110, L-111, L-112, G-5, G-12, G-14, G-15, L-90, G-8, G-2, L-71, L-70, L-39, G-5, L-69, L-79, L-38, G-3, G-4, G-6, G-13, L-74, L-64, L-75, L-40, G-11, G-9$

Table 4.24: 75-bus system– Optimal weights for reactive power performance indices

Bus no.	Weights	Bus no.	Weights	Bus no.	Weights
1	0.11991481E+00	6	0.58939597E+08	11	-0.33428567E+06
2	-0.51648134E+09	7	-0.74733740E+01	12	0.78182499E+08
3	0.17991880E+10	8	-0.10935711E+10	13	0.10000002E+01
4	0.83966756E+09	9	0.33335191E+03	14	0.11165636E+06
5	-0.58996782E+09	10	-0.15351267E+08	15	0.33874526E+09

(iii) The optimal weights calculated on a base case loading can be effectively used to define performance indices for small change in system loading conditions. The optimal weights are found to be effective up to ±3.0%, +3.0% and ±1.0% change in the 14-bus, 30-bus and 75-bus systems, respectively.

(iv) For voltage contingency selection, the voltage performance indices, in general, has provided better results as compared to the reactive power performance indices.

Chapter 5

A Genetic Algorithm Based Loss Minimization Technique

5.1 Introduction

In the present crisis of energy, all over the world, particularly in developing countries like India where transmission and distribution (technical) losses are quite high [124], the importance of reducing the system transmission loss is of great significance. This can be achieved by proper allocation of power outputs of sources. Optimal power flow (OPF) determines the optimal settings of outputs of sources in view of achieving certain objective(s). Some of the objectives considered in the formulation of the optimal power flow problems are the minimization of total fuel cost of thermal plants [10, 76, 96, 144, 145, 148], minimization of emission level [57], minimization of system transmission loss [26, 29, 33, 67, 86, 120, 129] or bus voltage deviations [7]. The review of various optimal power flow methods are reported in references [16, 73, 97, 137].

Loss minimization is a subproblem of the optimal power flow which is conventionally used to determine optimal settings of reactive power output of sources. It has also been termed as *optimal reactive power dispatch* (ORPD) problem. To determine the optimal power settings of real power output of sources, the *economic dispatch* subproblem of OPF has been utilized, which minimizes the total fuel cost of generation.

Many a time, particularly in India, the cost characteristics of generating units are not available. Hence, real power dispatch, based on economic criteria, can not be formulated. However, utilities require some guidelines to optimally adjust the real and reactive power

settings of sources. One possible criteria to decide the optimal settings of sources, in absence of cost characteristics, can be based on the system transmission loss minimization. Moreover, any reduction in the transmission loss adds to the load delivering capacity of the system and helps those utilities in meeting additional demands which are facing shortage of generation.

Several methods have been reported, in past, to solve the OPF problem. Some of them include classical method based on Lagrange multiplier approach [81, 109, 115, 142, 155], linear programming (LP) method [49, 59, 60, 89, 92], quadratic programing (QP) method [10, 41, 52], reduced gradient method of Dommel-Tinney [6], generalized reduced gradient method [107], differential injection method by Carpentier [42], Newton's method [40, 98, 139, 160], successive QP [66, 157], interior point method [117, 128, 135, 143] and continuation method [70, 87] etc.

Genetic algorithm (GA) [69] is becoming popular to solve the optimization problems mainly because of its robustness in finding optimal solution and ability to provide near optimal solution close to the global minimum. Genetic algorithms employ search procedures based on the mechanics of natural selection and survival of the fittest. They are often used as parameter search techniques which manipulates coding of the parameter set to find near optimal solution. GA can be used to find approximate global optimum of even those function having a large number of local optima. It has been recently applied to power system problems such as for load flow [106], optimal reactive power dispatch [138, 146], economic dispatch [136, 149], optimal hydro-generator control parameter tuning [126] and distribution system design and operational problems [119, 133, 153, 158].

In this Chapter, the loss minimization problem has been formulated to obtain the optimal settings of both real and reactive power outputs of the sources and has been solved using genetic algorithm. This formulation considers various system constraints such as limits on source outputs (P_G and Q_G) and bus voltage magnitudes (V). The results have been obtained on IEEE 14-bus & 30-bus systems and a practical 75-bus system derived from U.P. State Electricity Board network and compared with those obtained from Fletcher's quadratic programming (FQP) [52, 71] method.

5.2 Conventional Loss Minimization Model

Conventionally, a loss minimization problem is formulated as optimal reactive power dispatch problem. The optimal reactive power dispatch problem minimizes the total system real power transmission loss (P_L) to determine optimal settings of reactive power output of sources and transformer (OLTC) tappings. It can be mathematically written as

$$Minimize \quad P_L \tag{5.1}$$

subject to reactive power balance equation

$$\sum_{i=1}^{N_q} Q_{Gi} - Q_L - Q_D = 0 \tag{5.2}$$

and set of inequality constraints

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \qquad i = 1, \ldots ..N_q \tag{5.3}$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \qquad i = 1, \ldots ..N \tag{5.4}$$

$$t_i^{\min} \leq t_i \leq t_i^{\max} \qquad i = 1, \ldots ..N_a \tag{5.5}$$

where

Q_L	:	Total system reactive power loss
Q_{Gi}	:	Reactive power output of source-i
Q_D	:	Total reactive power demand of the system
V_i	:	Voltage magnitude at bus-i
t_i	:	On-load tap changer (OLTC) setting of transformer-i
N_q	:	Total number of reactive power sources
N	:	Total number of buses in the system
N_a	:	Total number of transformers with OLTC provision

The objective function P_L and reactive power loss Q_L has been expressed in several work using an exact loss formulation [2] as given below

$$P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} [\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - Q_jP_i)] \tag{5.6}$$

$$Q_L = \sum_{i=1}^{N} \sum_{j=1}^{N} [\gamma_{ij}(P_iP_j + Q_iQ_j) + \zeta_{ij}(Q_iP_j - Q_jP_i)] \tag{5.7}$$

where

$$\alpha_{ij} = \frac{r_{ij}}{V_i V_j} \cos(\delta_i - \delta_j)$$

$$\beta_{ij} = \frac{r_{ij}}{V_i V_j} \sin(\delta_i - \delta_j)$$

$$\gamma_{ij} = \frac{x_{ij}}{V_i V_j} \cos(\delta_i - \delta_j)$$

$$\zeta_{ij} = \frac{x_{ij}}{V_i V_j} \sin(\delta_i - \delta_j)$$

P_i : Net real power injection at bus-i
Q_i : Net reactive power injection at bus-i
$r_{ij} + jx_{ij}$: ijth element of Z_{bus} matrix

Other loss formulae for P_L and Q_L have also been used for the reactive power dispatch problem [95,132,142].

5.3 Proposed Optimal Power Flow Model

The proposed model of loss minimization problem has been formulated to obtain both real and reactive power settings of sources in view of minimizing the total system real power transmission loss subject to the system operating constraints. Mathematically, it can be written as

$$Minimize \;\; P_L \tag{5.8}$$

subject to real and reactive power balance equations

$$\sum_{i=1}^{N_g} P_{Gi} - P_L - P_D = 0 \tag{5.9}$$

$$\sum_{i=1}^{N_q} Q_{Gi} - Q_L - Q_D = 0 \tag{5.10}$$

and set of inequality constraints

$$P_{Gi}^{\min} \leq P_{Gi} \leq P_{Gi}^{\max} \qquad i = 1, \ldots .N_g \tag{5.11}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max} \qquad i = 1, \ldots .N_q \tag{5.12}$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \qquad i = 1, \ldots .N \tag{5.13}$$

$$t_i^{\min} \leq t_i \leq t_i^{\max} \qquad i = 1, \ldots ..N_a \tag{5.14}$$

where N_g is the total number of generating plants (real power sources) out of N_q reactive power sources. The objective function (real power loss) P_L and reactive power loss Q_L have been expressed using the exact loss formulae (equations (5.6) to (5.7)) in the present work.

5.4 Overview of Genetic Algorithm

5.4.1 General

Genetic algorithm is an optimization method based on the mechanics of natural selection and natural genetics. Its fundamental principle is that *the fittest member of population has the highest probability for survival.*

The most familiar conventional optimization techniques fall under two cotegories viz. calculus based methods and enumerative schemes. Though well developed, these techniques possess significant drawbacks. Calculus based optimization generally relies on continuity assumptions and existence of derivatives. Enumerative techniques rely on special convergence properties and auxiliary function evaluation. The genetic algorithm, on the other hand, works only with objective function information in a search for an optimal parameter set. The GA can be distinguished from other optimization methods by following four characteristics [69].

(i) The GA works on coding of the parameters set rather than the actual parameters.

(ii) The GA searches for optimal points using a population of possible solution points, not a single point. This is an important characteristic which makes GA more powerful and also results into implicit parallelism.

(iii) The GA uses only objective function information. No other auxiliary information (e.g. derivatives etc.) are required.

(iv) The GA uses probabilistic transition rules, not the deterministic rules.

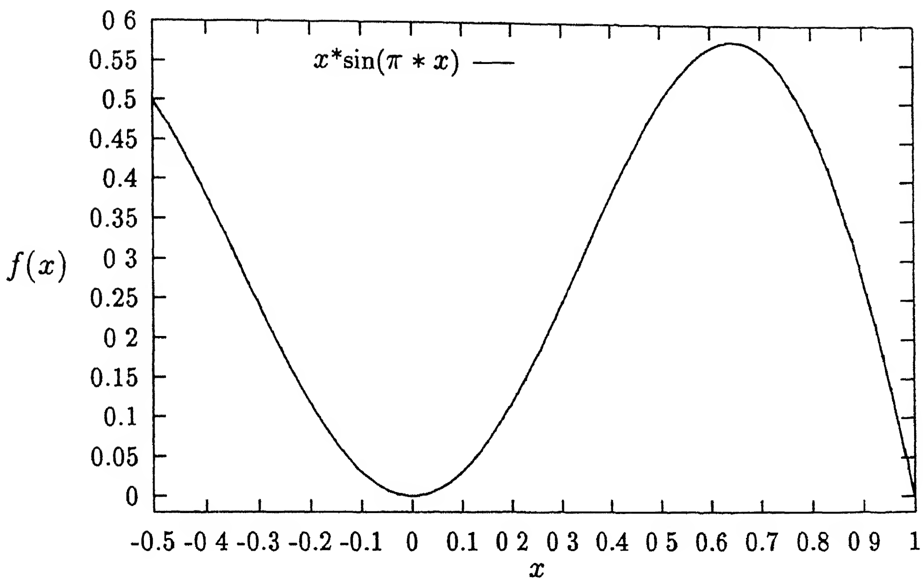

Figure 5.1: Graph of function f(x)

5.4.2 Components of Genetic Algorithm

Genetic algorithm is essentially derived from a simple model of population genetics. It has five following components [50]:

(i) Chromosomal *representation* of the variables characterizing an individual.

(ii) An *initial population* of individuals.

(iii) An *evaluation function* that plays the role of the environment, rating the individuals in terms of their *fitness* that is their aptitude to survive.

(iv) *Genetic operators* that determine the composition of a new population generated from the previous one by a mechanism similar to sexual reproduction.

(v) Values for the*parameters* that the GA uses.

These five components can be easily understood by considering optimization of a simple function. Consider a function $f(x)$ of single variable x which is shown in Fig. 5.1 and defined as,

$$f(x) = x.\sin(\pi x) \tag{5.15}$$

The problem is to find x in the range [-0.5,1.0] which maximizes the function f, i.e., to find x_0 such that

$$f(x_0) \geq f(x), \quad for\ all\ x \in [-0.5, 1.0] \tag{5.16}$$

It is relatively easy to analyze the function f. The zeros of the first derivative f' should be determined.

$$f'(x) = \sin(\pi x) + \pi.x \cos(\pi x) = 0 \tag{5.17}$$

or

$$\tan(\pi.x) = -\pi x \tag{5.18}$$

It is clear that the above equation has an infinite number of solutions

$$x_i = \begin{cases} \frac{2i-1}{2} + \epsilon_i & \text{for } i = 1, 2, \ldots \\ 0 & \text{for } i = 0 \\ \frac{2i+1}{2} - \epsilon_i & \text{for } i = -1, -2, \ldots \end{cases} \tag{5.19}$$

where ϵ_i represents decreasing sequences of real numbers approaching to zero.

The function f has two maxima at -0.5 and 0.5+ϵ_1 and two minima at x=0.0 and 1.0 in the range [-0.5,1.0]. The function reaches its global maximum at x = 0.6501 where $f(x) = 0.5719$ is slightly higher than $f(0.5) = 0.5$. The major components of GA to solve the problem are as follows.

5.4.2.1 Representation

Because GA is based on natural genetics, there exists strong analogies between genetic algorithm and natural genetics. In GA, the *features* characterizing an individual are often binary coded in bits (e.g. 0_s and 1_s) and concentrated as *string.* The strings are similar to chromosomes in biological systems, where the *chromosomes* are composed of genes which may take any of several forms called *alleles.*

The length of string depends on the precision required. In the above example, assume that the precision is required up to four place after the decimal point. The domain of the variable x has length 1.5. The precision requirement implies that the range [-0.5,1.0] should be divided into at least 1.5*10000 equal size ranges. This shows that 14 bits are required, since

$2^{13}(= 8192) < 15000 < 2^{14}(= 16384)$

The binary string $< a_{14}a_{13}......a_1 >$ can be converted at base 10 as

$$(< a_{14}a_{13}....a_1 >) = (\sum_{i=1}^{14} a_i.2^{i-1}) = x' \tag{5.20}$$

and the corresponding real number x will be

$$x = x'\frac{\text{length of domain}}{2^{\text{no. of bits}} - 1} + (\text{left boundary of domain}) \tag{5.21}$$

Thus, a chromosome (10000101110110) represents the number 0.31871, since

$x' = (10000101110110) = 8942$ and $x = -0.5 + 8942\frac{1.5}{2^{14}-1} = 0.31871$

The chromosomes (00000000000000) and (11111111111111) represent boundaries of the domain -0.50 and 1.0, respectively.

5.4.2.2 Initial Population

GA does not work with a single string but with a population of strings, which evolves iteratively by generating new individuals taking the place of their parents. To begin, the initial population is generated at random or through the use of specified information.

5.4.2.3 Evaluation Function

The performance of each structure of string is evaluated according to its *fitness*, which is defined as a non-negative figure of merit to be maximized. It is associated directly with the objective function value (f) in the optimization. GA treats the problem as a *black box* in which the input is the structure of the strings and the output is its fitness. Because GA proceeds only according to the fitness of the strings and not to other information, the properties of the fitness will influence the GA's performance.

The evaluation function F_e for binary vector C is equivalent to the function f

$$F_e(C) = f(x)$$

where the chromosome C coresponds to the real value x. The evaluation function plays the role of the environment, rating potential solutions in terms of their fitness. For example, three chromosomes

$$\begin{aligned} C_1 &= (10001011101101) \\ C_2 &= (00000011100000) \\ C_3 &= (11100000001111) \end{aligned}$$

correspond to values $x_1 = 0.3186, x_2 = -0.4795$ and $x_3 = 0.8140$, respectively. The evaluation function would rate them as follows

$$
\begin{aligned}
F_e(C_1) &= f(x_1) = 0.2682 \\
F_e(C_2) &= f(x_2) = 0.4785 \\
F_e(C_3) &= f(x_3) = 0.4491
\end{aligned}
$$

The chromosome C_2 is the best of the three chromosomes because its evaluation value is the highest.

5.4.2.4 Genetic Operators

With an initial population of individuals of various fitnesses, the operators of GA begins to generate a new and improved population from the old one. A simple genetic algorithm consists of three basic operators : reproduction, crossover and mutation.

Reproduction (Selection): Reproduction or selection is simply an operation, whereby an old string is copied into a *mating pool* according to its fitness. More highly fitted strings (i.e. with better values of the evaluation function) receive a higher number of copies in the next generation. There are many ways to do this. One commonly used technique is Roulette wheel parent selection.

Roulette wheel parent selection

The following steps are carried out in Roulette wheel parent selection algorithm.

(1) Sum the fitnesses of all the population members (say n in numbers). Call it as *total fitness.*

(2) Generate n random numbers(r_i) between 0 and the total fitness.

(3) Select a population member whose cumulative fitness obtained from adding its fitness to the fitnesses of the proceeding population members, is greater than or equal to r_i (i=1,...,n).

The effect of Roulette wheel parent selector is to return a randomly selected parent. Although this parent selection procedure is random, each parent's chance of being selected is directly proportional to its fitness. It is possible that the worst population member could be selected by this algorithm. Such an occurence would inhibit the performance of genetic algorithm using this selection techniques. But the odds of this happening in a population of any size are negligible [99].

Table 5.1: Roulette wheel parent selection

Chromosome(i)	1	2	3	4	5
Fitness(f_i)	0.1538	0.5352	0.0739	0.4805	0.3851
Running Total(Rf_i)	0.1538	0.6890	0.7629	1.2434	1.6285
percentage($\frac{f_i}{\sum f_i}.100$)	9.44	32.86	4.54	29.51	23.47

Table 5.2: Selection of chromosomes

Random Number(r_i)	0.250	1.173	0.567	1.189	0.294
Chromosomes chosen	2	4	2	4	2

This algorithm is referred to as Roulette wheel selection because it can be viewed as allocating pi-shaped slices on Roulette wheel to population members, with each slice proportional to the member's fitness. Selection of a population member to be a parent can then be viewed as a spin of the wheel. This parent selection technique has the advantage that it directly promotes reproduction of the fittest population members by biasing each member's chance of selection in accordance with its evaluation.

Table 5.1 shows the fitness of five chromosomes, running total of their fitness and percentage of fitness. Fig. 5.2 shows the Roulette wheel and Table 5.2 shows the chromosome that would be chosen by the Roulette wheel algorithm using these fitness values for each of 5 randomly generated numbers. This technique can be used for only those chromosomes whose fitness values are positive numbers.

Crossover: Crossover is a randomized yet structured recombination operation. Simple crossover may proceed in two steps. Firstly, the newly reproduced strings in the mating pool are mated at random. Secondly, crossover of each pair of strings are done as follows:

(i) An integer position p along string is selected at random in the intervals [1,L-1], where L is the string length.

(ii) Two new strings are created by swapping all characters between position 1 and p inclusively.

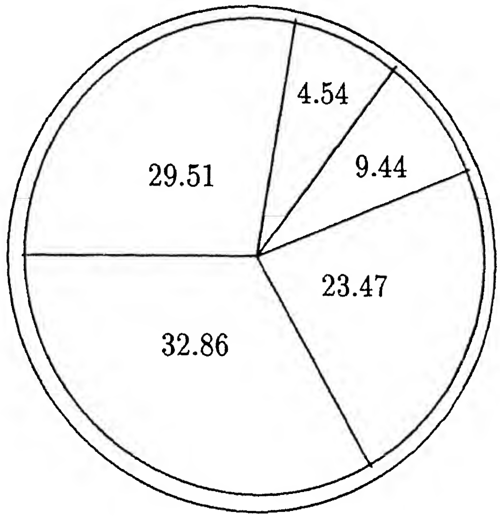

Figure 5.2: Roulette wheel

Let us consider the crossover operator on chromosomes C_2 and C_3. Assume that the crossover point was (randomly) selected after the 5th gene

$$C_2 = (00000 \quad 011100000)$$
$$C_3 = (11100 \quad 000001111)$$

The two resulting offspring will be

$$C_2' = (00000 \quad 000001111)$$
$$C_3' = (11100 \quad 011100000)$$

The offspring evaluate to

$$Fe(C_2') = f(-0.4986) = 0.4986$$
$$Fe(C_3') = f(0.8331) = 0.4171$$

This shows that offspring C_2' has a better evaluation than both of its parents. Crossover exchanges corresponding genetic material from two parent chromosomes, allowing beneficial genes of different parents to be combined in their offsprings.

Mutation: Reproduction and crossover effectively search and recombine the existing chromosomes. However, they do not create any new genetic material in the population. Mutation is capable of overcoming this shortcoming. It is an occasional random alteration of a string position. In the binary string representation, this simply means changing a 1 to 0 or vice versa. This random mutation provides background variation and occasionally introduces beneficial materials into the population.

Consider the mutation operation on a chromosome C_3 and say that the 3rd gene is selected for mutation then

$$C_3'' = (11000000001111)$$

The corresponding values of $x'' = 0.6264$ and $Fe(x'') = 0.5777$ show an improvement over the original value of $Fe(C_3) = 0.4491$.

5.4.2.5 Parameter Values

Like other stochastic methods, GA requires a number of parameters such as population size, probability of crossover, probability of mutation that must be selected. Usually, relatively small population size, high crossover probability (P_c), and low mutation probability (P_m) inversely proportional to the population size, are recommended [69]. The selection of optimal values of these parameters is generally done through hit and trails. However, the value of P_c generally lies between 0.6 to 0.8 and of P_m between 0.0001 to 0.1 [45,121]. A general flow chart of genetic algorithm including all these components is given in Fig. 5.3.

5.4.3 Some Other Aspects of GA

The theoretical foundation of GA is based on a fundamental theorem as described in Appendix-A. Some other aspects of genetic algorithms are explained below.

5.4.3.1 Multiple Path Search

Most of the optimization approaches are single path search algorithms. Starting from an initial condition, they improve the state variables in every iteration. There is a single path from an initial condition through a converged solution. The multiple path search has various possible solutions in every iteration. In GA, the iteration and number of these states are called generation and populations, respectively. Every intermediate point in the same generation can interchange information with each other. The larger the population, the greater the possibility of converging to the global optimum. Although there is no guarantee that it will be global, it is more likely to be so. The multiple search may be essential in long range planning for power systems, since there is no promising initial conditions in significantly changed systems.

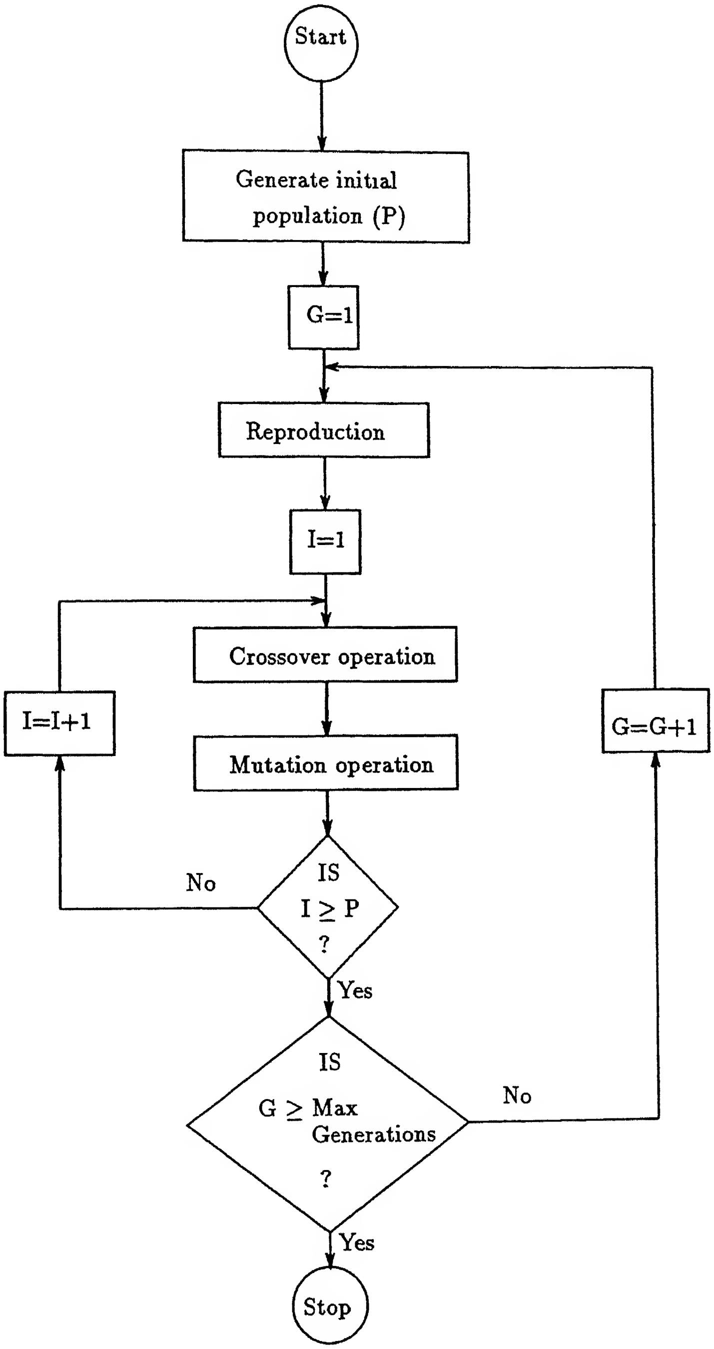

Figure 5.3: A general flow chart of genetic algorithm

5.4.3.2 Fitness Function

In many problems, the objective is more naturally stated as the minimization of some cost function $f(x)$ rather than the maximization of some utility or profit function $u(x)$. Even if the problem is in maximization form, this does not guarantee that the function will be non-negative for all x. A fitness function must be a non-negative figure of merit. Hence, it is often necessary to map the objective function to a fitness function form. In normal operations research work, to transform a minimization problem to a maximization problem, cost function can be multiplied by minus one (-1). In GA, this may not be sufficient because it is not guaranteed to be non-negative in all instances. The following cost-to-fitness transformation is commonly used.

$$F(x) = \begin{cases} C_{max} - f(x) & where \;\; f(x) < C_{max} \\ 0 & otherwise \end{cases} \tag{5.22}$$

There are a variety of ways to choose the coefficient C_{max}. C_{max} may be taken as an input coefficient, as the largest f value observed thus far, as the largest value in the current population, or the largest of the last k generations. Perhaps more appropriately, C_{max} should vary depending on population variance.

Some additional measures are helpful in defining the fitness function known as scaling mechanism.

1. Linear Scaling: In this method the actual chromosome's fitness is scaled as

$$F_i = af_i + b \tag{5.23}$$

The parameters a and b are normally selected so that the average fitness is mapped to itself and the best fitness is increased by a desired multiple of the average fitness. This mechanism, though quite powerful, can introduce negative evaluation values that must be dealt with. In addition, the parameters a and b are normally fixed for the population life and are not problem dependent.

2. Sigma Truncation: This method was designed as an improvement of linear scaling both to deal with negative evaluation values and to incorporate problem dependent information into the mapping itself. The new fitness is calculated according to

$$F_i = f_i + (\bar{f} - c.\sigma) \tag{5.24}$$

5.5 Loss Minimization Solution using Genetic Algorithm

Some of the considerations in implementing the genetic algorithm to the solution of proposed optimal power flow model formulated in section 5.3 as loss minimization problem are as follows:

5.5.1 Fitness Function

The OPF model described in section 5.3 has two equality constraints and four sets of inequality constraints. The equality constraints (equations (5.9) and (5.10)) have been included in the objective function using Lagrange multipliers λ_1 and λ_2. The augmented objective functions can be written as

$$f_a = P_L - \lambda_1 \left(\sum_{i=1}^{N_g} P_{Gi} - P_L - P_D \right) - \lambda_2 \left(\sum_{i=1}^{N_q} Q_{Gi} - Q_L - Q_D \right) \tag{5.26}$$

The functional inequalities, in general, can be expressed in the upper bound and lower bound forms as

$$r_i \leq r_i^{max} \quad i = 1, ..., p \tag{5.27}$$

$$s_i \geq s_i^{min} \quad i = 1, ..., q \tag{5.28}$$

These can be included in the objective function using a set of penalty functions, as given below

$$f' = f_a + w_1 \sum_{i=1}^{p} (r_i^{max} - r_i)^2 + w_2 \sum_{i=1}^{q} \left(s_i - s_i^{min} \right)^2 \tag{5.29}$$

where w_1 and w_2 are the constant penalty factors associated with upper and lower bound inequalities, respectively. The Lagrange multipliers λ_1 and λ_2, however, have been taken as variables, to be determined by GA.

In the present work, the OPF model has been used to obtain the optimal real power (P_G) and reactive power (Q_G) outputs of sources. The transformer taps (t) have not been considered in the model and have been assumed to be fixed at their base case values.

Further, all the functional inequalities are required to be expressed in terms of variables P_G and Q_G. Voltage constraints (equation (5.13)) have been considered as functional inequalities which can be expressed in terms of real and reactive power outputs of sources using sensitivity matrix $[S]$ as defined in the section 3.4 as following.

$$\begin{bmatrix} \Delta\delta \\ \Delta V/V \end{bmatrix} = \begin{bmatrix} S_1 & S_2 \\ S_3 & S_4 \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{5.30}$$

which provides

$$\Delta V = V^0 \begin{bmatrix} S_3 & S_4 \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{5.31}$$

Using above linearized relationship for ΔV, the inequality constraints for bus voltage limits can be written as

$$V^{min} \leq V^0[1 + S_3(P_G - P_G^0) + S_4(Q_G - Q_G^0)] \leq V^{max} \tag{5.32}$$

where $(.)^0$ are the base values and $[S_3]$ & $[S_4]$ are the submatrices of sensitivity matrix [S] which can be computed at the base operating point as given in section 3.4 of Chapter 3.

Since GA works on maximization principle and the objective function should be non-negative, the following fitness function has been used.

$$g = \begin{cases} F - f' & when \;\; f' < F \\ 0 & otherwise \end{cases} \tag{5.33}$$

Where F is a large baseline value. The *GAucsd* program [140] has been used to solve the OPF problem which uses a sigma scaling for selecting the value of F. F is selected as the average value of objective function f' plus a factor derived from its standard deviation as given in section 5.4.3.2.

5.5.2 GA Parameters

The GA routine requires fixing of its parameters viz crossover probability (P_c), mutation probability (P_m), population size and string length. The values of P_c and P_m were selected by plotting loss figures obtained from OPF as function of these parameters. Experimentation with different values of P_m, P_c and population size were done for all the three systems and the values which resulted into minimum objective function were selected. The following parameters were selected for the study.

(a) IEEE 14-bus system

P_c	=	0.650
P_m	=	0.00200
No. of bits per string	=	8
Population size	=	100

(b) IEEE 30-bus system

P_c	=	0.600
P_m	=	0.00075
No. of bits per string	=	8
Population size	=	130

(c) 75-bus UPSEB system

P_c	=	0.600
P_m	=	0.00056
No. of bits per string	=	5
Population size	=	1200

The number of bits per string was selected based on accuracy required. For IEEE 14-bus and 30-bus systems it was considered up to second place after decimal point. However, it was taken only up to first place of decimal point for the 75-bus UPSEB system. The restriction on accuracy was in view of limiting the computational time, which increases as the number of bits increases.

5.5.3 Solution Steps

Following major steps are involved in solving the optimal power flow problem by genetic algorithm.

Step–1: With the given network conditions, run a base load flow. Calculate the loss coefficients $(\alpha, \beta, \gamma, \zeta)$ of equations (5.6) to (5.7) and sensitivity matrix $[S]$.

Step–2: Run GA to obtain optimal real and reactive power settings of sources.

Step–3: Fixing the outputs of sources as obtained in step-2 (except slack bus), run the final load flow.

5.6 Numerical Results and Discussions

The proposed optimal power flow model based on GA has been tested on IEEE 14-bus and 30-bus systems, and a practical Indian system derived from U.P. State Electricity Board (UPSEB) network which are given in Appendices-B, C and D, respectively. The 75-bus system represents all 220 kV and 400 kV buses of UPSEB network and contains 114 lines and 15 generators. The results have also been obtained with Fletcher's quadratic

programming (FQP) method for optimization [52,71] and compared for the following two case studies.

Study-1 : Real power loss minimization without considering voltage constraints.

Study-2 : Real power loss minimization with voltage constraints.

The upper and lower limits of bus voltage magnitudes were taken as 1.10 and 0.90 pu for IEEE 14-bus & 30-bus systems and 1.07 & 0.95 pu for 75-bus system. A comparison of total transmission loss value obtained after solving the loss minimization problem using GA and FQP are given in Table 5.3.

The optimal values of real and reactive power outputs (in pu) of sources for both the case studies are presented in Table 5.4 for IEEE 14-bus system, in Table 5.5 for IEEE 30-bus system and in Table 5.6 for 75-bus system. The bus voltage magnitudes obtained by the two methods in two case studies are given in Table 5.7, Table 5.8 and Table 5.9 for the 14-bus, 30-bus and 75-bus systems, respectively.

From Table 5.3, it is observed that the GA based methodology is able to minimize the transmission loss (in MW), in almost all the test cases, to lower values as compared to those obtained by the FQP method. The loss reduction in study-2 is approximately 47%, 54 % and 8.1% in IEEE 14-bus, IEEE 30-bus and 75-bus UPSEB systems from their base values. In the study-1, though the loss reduction is more significant, voltages at some of the buses violated their limits. From Tables 5.7, 5.8 and 5.9, it is observed that the voltage at those buses which were violating the operating limits in the study-1, were brought down within their acceptable limits in study-2.

The transmission loss in IEEE 30-bus system by solving only optimal reactive power dispatch problem using GA [138] was also obtained. It was found to be 15.20 MW which is quite close to the base case value (15.32 MW) and much higher as compared to 7.57 MW obtained with the proposed method considering both real and reactive power optimization.

5.6.1 Economic Benefits of Loss Minimization

In order to appreciate the economic benefits offered by the proposed loss minimization technique, a calculation of energy saving and associated financial benefit was done. The transmission loss reduction in 75-bus system was 16.31 MW corresponding to a peak load condition. The load factor (LF) of UPSEB is approximately 0.53 and energy generated

Table 5.3: Comparison of system transmission loss in MW

Method	14-bus system		30-bus system		75-bus system	
	Study-1	Study-2	Study-1	Study-2	Study-1	Study-2
Base case	11.61	11.61	15.32	15.32	200.80	200.80
FQP	6.43	6.33	6.83	7.57	181.85	184.57
GA	6.44	6.20	6.82	7.05	167.97	184.49

Table 5.4: 14-bus system– Optimal settings of sources (in pu)

Gen. No.	Base case		FQP				GA			
			Study-1		Study-2		Study-1		Study-2	
	P_G	Q_G	P_G	Q_G	P_G	Q_G	P_G	Q_G	P_G	Q_G
1	2.106	-.171	0.654	-.362	0.653	-.034	0.642	-.360	0.646	-.159
2	0.400	0.306	1.000	0.295	1.000	0.191	1.004	0.038	1.000	0.302
3	0.200	0.190	1.000	0.185	1.000	-.003	1.000	0.198	1.003	-.029
4	—	0.199	—	0.185	—	0.205	—	0.316	—	0.313
5	---	0.162	—	0.130	—	0.075	—	0.239	—	-.010

per annum is approximately 28000 MU [141]. The corresponding loss load factor (LLF) and percentage energy saving can be calculated by following formulae [142].

$$LLF = 0.2(LF) + 0.8(LF)^2 = 0.33 \tag{5.34}$$

$$\%\ \text{Energy saving} = \frac{\text{MW loss saved}}{\text{MW power dispatched}} . \frac{LLF}{LF} .100 \tag{5.35}$$

The annual saving in energy due to the loss reduction is found to be 49 MU. If the cost of electricity is considered as Rs 1.0 per unit, the money saved per annum will be approximately Rs 4.9 crores.

5.7 Conclusions

This Chapter has presented a new optimal power flow model for both real and reactive power dispatch considering loss minimization as objective. The OPF was solved using genetic algorithm on IEEE 14-bus, IEEE 30-bus and 75-bus UPSEB systems. The test results reveal the following :

Table 5.5: 30-bus system– Optimal settings of sources (in pu)

Gen. No.	Base case		FQP				GA			
			Study-1		Study-2		Study-1		Study-2	
	P_G	Q_G	P_G	Q_G	P_G	Q_G	P_G	Q_G	P_G	Q_G
1	2.385	-.172	0.566	-.468	0.500	0.113	0.499	-.132	0.500	0.173
2	0.400	0.523	1.162	0.338	1.166	0.500	1.177	0.282	1.171	0.098
3	0.200	0.195	1.172	0.317	1.233	-.053	1.229	0.332	1.239	0.177
4	--	0.228	—	0.240	—	0.053	—	0.208	—	0.164
5	—	0.358	—	0.250	—	0.400	—	0.175	—	0.256
6	—	0.194	—	0.240	—	0.024	—	0.130	—	0.156

Table 5.6: 75-bus system– Optimal settings of sources (in pu)

Gen. No.	Base case		FQP				GA			
			Study-1		Study-2		Study-1		Study-2	
	P_G	Q_G	P_G	Q_G	P_G	Q_G	P_G	Q_G	P_G	Q_G
1	7.757	0.354	4.954	0.098	5.164	0.581	4.069	-.840	7.160	-.538
2	2.600	1.046	1.506	0.960	1.320	0.800	2.878	0.371	2.010	0.541
3	1.800	0.659	2.000	0.830	2.000	0.830	1.948	0.328	1.410	0.345
4	1.000	0.528	1.700	0.570	1.700	0.600	1.694	0.350	1.400	0.276
5	1.800	0.232	2.400	0.310	2.400	0.310	2.328	0.034	2.110	0.092
6	1.200	0.134	1.200	0.200	1.200	0.200	1.193	0.057	1.130	0.118
7	0.600	0.083	1.000	0.135	1.000	0.147	0.947	0.147	0.820	0.009
8	0.800	0.744	1.000	0.680	1.000	0.680	0.969	0.584	0.830	0.538
9	5.500	1.289	5.700	0.684	5.700	0.972	5.478	0.477	5.630	1.379
10	0.800	0.312	1.300	0.560	1.300	0.560	1.108	0.404	0.860	0.466
11	1.090	0.611	2.000	0.859	2.000	0.692	2.000	0.621	1.420	0.921
12	18.00	2.124	18.00	0.000	18.00	0.000	18.00	0.228	18.00	0.484
13	9.000	1.101	9.000	1.695	9.000	1.925	9.000	0.367	9.000	1.741
14	1.500	0.361	1.500	0.193	1.500	0.242	1.500	0.520	1.500	0.465
15	4.540	-.127	4.540	0.350	4.540	0.350	4.540	0.027	4.540	0.016

Table 5.7: 14-bus system– Voltage magnitudes (in pu)

Bus No.	Base case	FQP		GA	
		Study-1	Study-2	Study-1	Study-2
1	1.060	1.060	1.060	1.0600	1.060
2	1.045	1.067	1.080	1.0651	1.100
3	1.070	1.108	1.080	1.1231	1.091
4	1.010	1.035	1.045	1.0515	1.074
5	1.090	1.106	1.086	1.1456	1.079
6	1.064	1.086	1.074	1.1089	1.081
7	1.057	1.076	1.062	1.0969	1.072
8	1.030	1.060	1.064	1.0678	1.082
9	1.025	1.055	1.058	1.0644	1.076
10	1.051	1.073	1.056	1.0927	1.066
11	1.057	1.085	1.062	1.1026	1.073
12	1.055	1.093	1.065	1.1086	1.076
13	1.050	1.085	1.058	1.1011	1.069
14	1.036	1.062	1.041	1.0850	1.052

(i) The proposed GA based OPF model results into substantial reduction in system transmission loss in all the three systems and is capable of handling the system constraints effectively in its model.

(ii) The loss reduction using the proposed GA based loss minimization model is more as compared to those obtained with only reactive power rescheduling [138]. The loss value is even lesser than those obtained with the Fletcher's quadratic programming method.

(iii) In Indian systems, since the cost characteristic of the generators are normally not available, the present OPF model is more relevant and can be used for rescheduling of both real and reactive power outputs of the sources.

(iv) The loss minimization results, if implemented, will result into significant annual saving in the energy, thus offering the economic benefit.

Table 5.8: 30-bus system– Voltage magnitudes (in pu)

Bus No.	Base case	FQP		GA	
		Study-1	Study-2	Study-1	Study-2
1	1.060	1.060	1.100	1.060	1.060
2	1.045	1.074	1.095	1.061	1.050
3	1.010	1.078	1.047	1.059	1.035
4	1.082	1.142	1.061	1.109	1.078
5	1.010	1.042	1.059	1.018	1.010
6	1.071	1.135	1.057	1.085	1.072
7	1.040	1.100	1.052	1.071	1.048
8	1.024	1.086	1.041	1.056	1.034
9	1.046	1.105	1.053	1.068	1.052
10	1.079	1.146	1.110	1.119	1.097
11	1.015	1.062	1.053	1.043	1.028
12	1.002	1.048	1.045	1.026	1.012
13	1.010	1.065	1.048	1.045	1.027
14	1.031	1.092	1.040	1.055	1.038
15	1.027	1.088	1.038	1.052	1.035
16	1.029	1.090	1.041	1.056	1.038
17	1.020	1.082	1.036	1.051	1.030
18	1.013	1.076	1.027	1.042	1.022
19	1.009	1.071	1.023	1.038	1.018
20	1.012	1.074	1.027	1.042	1.021
21	1.015	1.078	1.032	1.047	1.026
22	1.017	1.080	1.034	1.049	1.028
23	1.021	1.083	1.035	1.049	1.030
24	1.021	1.085	1.040	1.054	1.032
25	1.052	1.118	1.080	1.089	1.067
26	1.035	1.102	1.064	1.073	1.051
27	1.023	1.062	1.062	1.047	1.034
28	1.012	1.070	1.048	1.050	1.030
29	1.060	1.128	1.095	1.101	1.079
30	1.050	1.118	1.084	1.091	1.068

Table 5.9: 75-bus system– Voltage magnitudes (in pu)

Bus No.	Base case	FQP		GA	
		Study-1	Study-2	Study-1	Study-2
1	1.030	1.030	1.042	1.030	1.020
2	1.050	1.053	1.049	1.047	1.038
3	1.030	1.042	1.034	1.060	1.034
4	1.050	1.063	1.052	1.127	1.067
5	1.050	1.070	1.054	1.123	1.070
6	1.050	1.074	1.058	1.126	1.076
7	1.050	1.069	1.056	1.146	1.071
8	1.050	1.056	1.043	1.113	1.056
9	1.050	1.039	1.050	1.049	1.058
10	1.020	1.032	1.023	1.074	1.051
11	1.020	1.060	1.042	1.071	1.070
12	1.050	0.958	0.951	1.016	1.041
13	1.050	0.981	0.978	1.018	1.060
14	1.030	1.035	1.024	1.126	1.068
15	1.051	1.044	1.030	1.097	1.058
16	1.026	1.029	1.029	1.037	1.024
17	1.027	1.027	1.033	1.041	1.029
18	1.015	1.020	1.012	1.052	1.025
19	1.000	1.011	1.007	1.039	1.021
20	0.996	1.010	1.001	1.034	1.023
21	1.029	1.024	1.009	1.106	1.048
22	1.032	1.035	1.021	1.113	1.060
23	1.013	0.995	0.987	1.054	1.036
24	1.010	1.004	0.995	1.055	1.028
25	1.026	1.022	1.008	1.105	1.049
26	0.999	0.991	0.983	1.041	1.017
27	0.999	0.993	0.985	1.041	1.015
28	1.028	1.030	1.017	1.107	1.051
29	1.036	1.038	1.024	1.117	1.063
30	1.031	1.026	1.012	1.108	1.051
31	1.043	1.056	1.041	1.121	1.065
32	1.042	1.055	1.039	1.121	1.065
33	1.045	1.055	1.041	1.323	1.069
34	1.021	1.026	1.013	1.088	1.032
35	1.034	1.029	1.035	1.042	1.034
36	0.998	1.008	1.007	1.030	1.014
37	0.988	0.988	0.988	1.009	0.992

Table ... Contd.

Table 5.9 (Contd.) ...

Bus No.	Base case	FQP		GA	
		Study-1	Study-2	Study-1	Study-2
38	1.047	1.050	1.036	1.130	1.073
39	1.037	1.043	1.028	1.121	1.062
40	0.998	1.024	1.010	1.042	1.037
41	1.037	0.962	0.955	1.018	1.041
42	1.038	0.964	0.958	1.017	1.043
43	1.030	1.031	1.018	1.114	1.056
44.	1.062	1.041	1.027	1.101	1.062
45	1.018	1.047	1.034	1.109	1.074
46	0.986	0.989	0.989	1.001	0.986
47	1.009	1.012	1.005	1.048	1.021
48	0.980	1.008	0.994	1.026	1.021
49	0.970	0.998	0.983	1.016	1.011
50	0.992	1.001	0.997	1.022	0.998
51	0.987	0.981	0.972	1.032	1.004
52	0.987	0.982	0.972	1.034	1.005
53	1.027	1.024	1.010	1.105	1.047
54	1.016	1.015	1.002	1.082	1.036
55	1.022	1.002	0.988	1.068	1.023
56	1.026	1.026	1.013	1.107	1.050
57	1.014	1.013	0.998	1.096	1.037
58	1.014	1.014	0.999	1.098	1.038
59	1.015	1.015	1.000	1.098	1.038
60	1.011	1.008	0.993	1.092	1.035
61	1.026	1.026	1.011	1.105	1.047
62	1.031	1.038	1.022	1.110	1.052
63	1.017	1.006	0.992	1.072	1.026
64	0.977	0.992	0.983	1.017	1.006
65	1.028	1.023	1.009	1.105	1.048
66	0.984	0.999	0.990	1.024	1.012
67	1.008	1.005	0.996	1.053	1.026
68	1.007	1.010	1.002	1.045	1.018
69	0.962	0.963	0.963	0.984	0.967
70	1.010	1.007	0.992	1.092	1.034
71	0.997	0.994	0.985	1.039	1.013
72	1.012	1.008	0.994	1.094	1.036
73	1.019	1.041	1.028	1.104	1.071
74	1.013	0.993	0.984	1.053	1.036
75	1.038	1.040	1.026	1.120	1.066

Chapter 6

Corrective Action Planning to Enhance Voltage/Reactive Power Security

6.1 Introduction

For secure operation of a power system, it is essential to modify the dispatch philosophy such that it ensures the normal operation of the system even when a contingency takes place. Many a times, the solution of optimal power flow (OPF) no more remains feasible, specially, while considering the severe contingency cases. The available controls in such a situations are unable to retain the system in normal state.

A feasible (secure) region, in a multi-dimensional parameter space, can be defined as the set of points where system states (eg. line flows, bus voltage magnitudes) are within their limits. In other words if operating limits of one or more variables are violated, it is said to lie in infeasible (insecure) region.

Very few works are available in literature for handling the infeasible OPF or divergent power flow cases. To ensure feasible operation of the system, Monticelli et al. [51] had suggested the load curtailment and Burchett et al. [34] had proposed to use phantom generators at selected buses in the network which remain idle in normal operating condition. If a particular case becomes infeasible during optimization, the phantom generator is called upon to inject reactive power at the point of maximum need. Granville et al. [156] had used an auxiliary optimization problem of minimizing the fictitious reactive

power injections placed at all the buses which helps the user to determine the candidate buses for reactive power source installation. They call this preliminary step as *Feasibility Analysis.*

To ensure the security of the system, it is important to plan for the corrective control actions to bring the system back into normal state or in a feasible constrained region. Proper allocation and actual requirement of controls are essential before running a security constrained optimal power flow (SCOPF) algorithm. In this Chapter, an effective method to measure the degree of infeasibility and to plan the corrective actions for bringing the system into normal state, with switching of reactive power devices, has been developed.

A general flow chart of the security constrained optimal power flow utilizing the corrective action planning is presented in Fig. 6.1. Block-I and II of the flow chart pertains to the security analysis of the system. If any of the contingencies result into violation of operating limits (block-III) and it is not possible to bring them within limit with available controls (block-IV), corrective control actions are required to be planned (block-V) before executing the security constrained optimal power flow (block-VI).

The present work has tried to develop the methodology to detect whether the system can be brought to normal state with available controls (block-IV) and to plan for the corrective control actions otherwise. Overbye [151] introduced an algorithm to quantify the degree of unsolvability of power flow problems and to determine the controls to return to solvability [162] which is derived from a similar measure presented in reference [125]. This approach has been extended in this Chapter for security enhancement to achieve feasibility of optimal power flow solution. The results have been demonstrated on IEEE 14-bus and 30-bus systems, and a 75-bus system derived from U.P. State Electricity Board (UPSEB) network.

6.2 Problem Formulation

The distance (Euclidean norm) in parameter space between any infeasible (insecure) point and the closest point on feasible (secure) hypersurface σ has been used as a measure of infeasibility. In a given operating condition, system states can lie in any of the three regions shown in Fig. 6.2. The states can lie in either unsolvable region-I where load flow solution does not exist (Transient state) or in an infeasible region-II where load flow solution exists but system operating constraints are not satisfied or in a feasible region-III

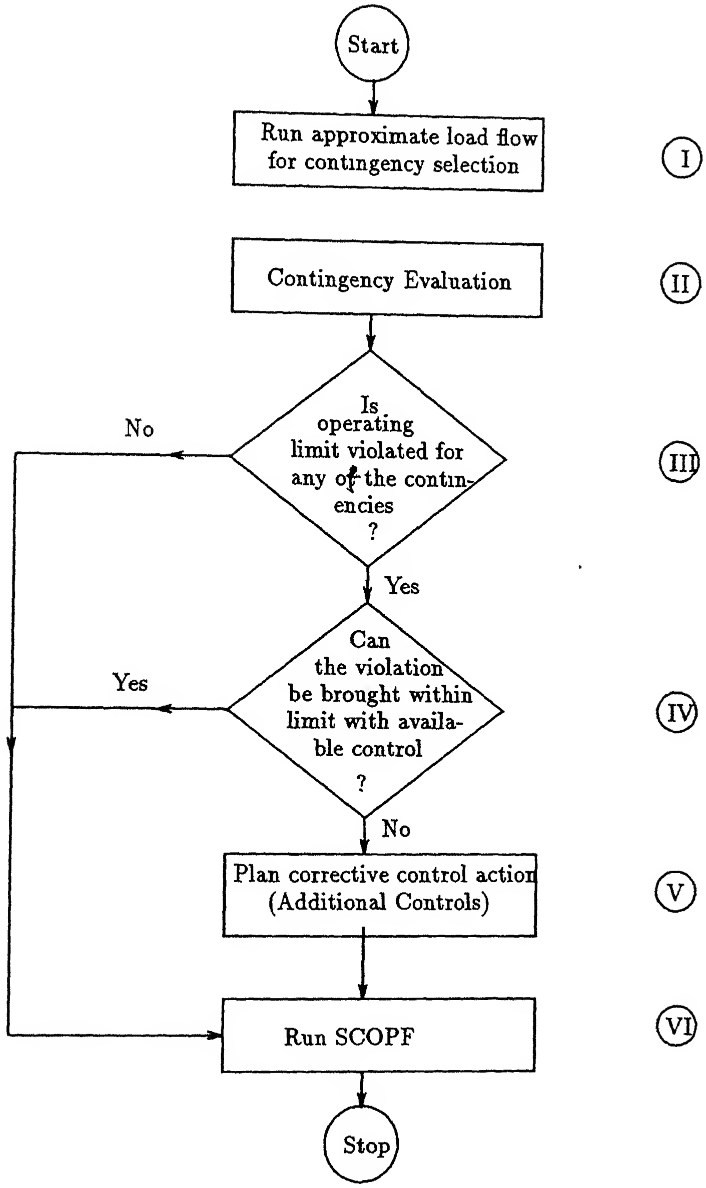

Figure 6.1: Flow chart of security constrained optimal power flow

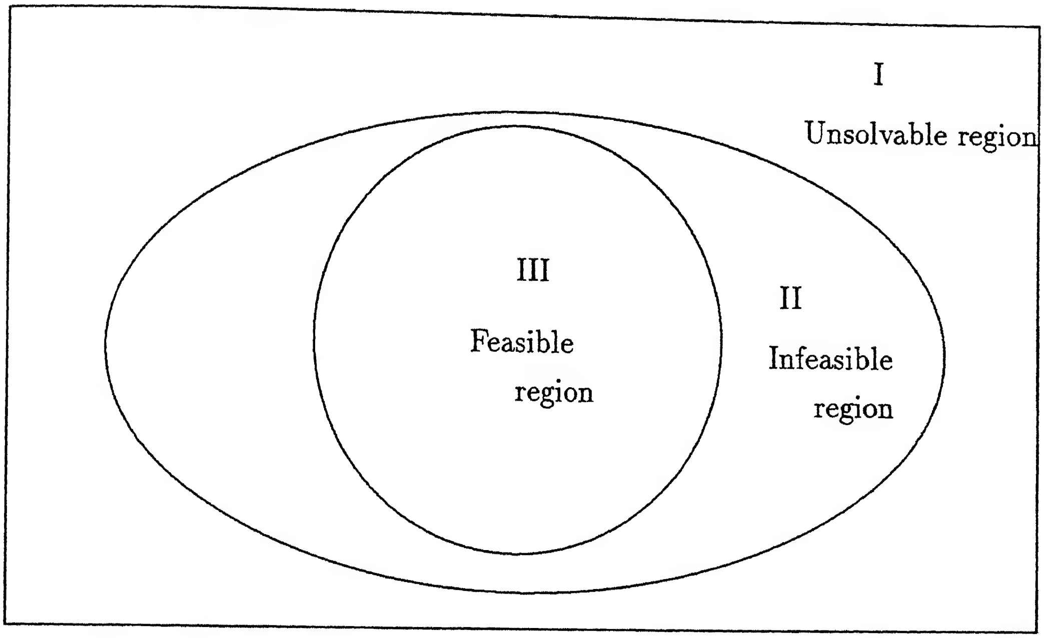

Figure 6.2: Schematic representation of the operating regions

where operating constraints are satisfied along with existence of the load flow solution.

For an N-bus system with bus-1 being slack, 2,...,N_q being the P-V type buses and N_q+1 to N the P-Q type buses, the power flow equations can be expressed as following

$$f_{P_i}(\mathbf{V},\delta) = \sum_{j=1}^{N} V_i V_j \left[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)\right] \qquad i = 2,...,N \tag{6.1}$$

$$f_{Q_i}(\mathbf{V},\delta) = \sum_{j=1}^{N} V_i V_j \left[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)\right] \qquad i = N_q+1,...,N \tag{6.2}$$

where $\mathbf{V}$ and δ are voltage magnitude and angle vectors. If $\mathbf{S}$ is a vector of real power injections at all the buses except the slack bus and the reactive power injections at only load (P-Q) buses, then equations (6.1) and (6.2) can be written in vector form as following

$$\mathbf{S} - \mathbf{f}(\mathbf{V},\delta) = 0 \tag{6.3}$$

where $\mathbf{S} = [P_2, P_3, ..., P_N, Q_{N_q+1}, Q_{N_q+2}, ..., Q_N]^T$

If power flow problem, defined by equation (6.3), has no real solution (lying in region-I of Fig. 6.2) or it has a solution with violating operating limits such as voltage limits (lying in region-II of Fig. 6.2), it has been called to have as infeasible solution in the present work. The problem has been reformulated as a standard constrained minimization problem with

an objective function defined as one half the square of the power mismatches to find the closest feasible point in parameter space and is expressed as

$$F(\mathbf{V},\delta) = \frac{1}{2}[\mathbf{f}(\mathbf{V},\delta) - \mathbf{S}]^T[\mathbf{f}(\mathbf{V},\delta) - \mathbf{S}] \tag{6.4}$$

subject to the operating constraints

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 2,\ldots..N \tag{6.5}$$

$$\delta_i^{\min} \le \delta_i \le \delta_i^{\max} \qquad i = 2,\ldots..N \tag{6.6}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \quad i = 1,\ldots..N_g \tag{6.7}$$

where Q_{Gi} is the reactive power generation of source-i which is N_g in number. The objective function F will be greater than zero for all $\mathbf{V}$ and δ lying into infeasible region and will be equal to zero in the feasible region. The above equations (6.4) to (6.7) form a constrained power flow (CPF) problem.

6.3 Degree of Infeasibility

Let $\mathbf{x}^*$ $(\mathbf{V}^*, \delta^*)$ be defined as the value of the voltage magnitude and angle vectors corresponding to the minima of the objective function $F(\mathbf{x})$; thus, $\mathbf{x}^*$ can be thought of as the best possible feasible solution to the equations (6.4) to (6.7). Define

$$\mathbf{S}^* = f(\mathbf{x}^*) \tag{6.8}$$

to be the point in the parameter space corresponding to $\mathbf{x}^*$.

The closest point on the surface σ to $\mathbf{S}$ is $\mathbf{S}^*$. It follows from the definition of $\mathbf{x}^*$, that minimizing equation (6.4), is equivalent to minimizing the Euclidean norm $||\mathbf{S} - \mathbf{S}^*||$. The optimal direction to move in parameter space to return to feasible region is then given by vector $[\mathbf{S} - \mathbf{S}^*]$ which contains real and reactive power mismatches at each bus. Providing controls at each bus to force the mismatches to zero is not practically possible. An alternate way of attaining the feasibility is described in section 6.5.

The degree of infeasibility can be measured by Euclidean distance between the closest point S^* on the surface σ and $\mathbf{S}$ which is given by

$$
\begin{aligned}
d(\mathbf{S}) &= \|\mathbf{S}^{*} - \mathbf{S}\| \\
&= \sqrt{[\mathbf{S}^{*} - \mathbf{S}]^{T}[\mathbf{S}^{*} - \mathbf{S}]}
\end{aligned}
\tag{6.9}
$$

Since only voltage security or feasibility has been studied in the present work, the Euclidean distance of reactive power at the load buses has been considered. Hence, the above equation (6.9) can be rewritten as

$$
d(Q) = \sqrt{\sum_{i=N_q+1}^{N} [f_{Q_i}(\mathbf{V}^{*}, \delta^{*}) - Q_i]^2} \tag{6.10}
$$

6.4 Eigenvalue Analysis to Decide Optimal Control Direction

The eigenvalue analysis of the power flow Jacobian matrix near the point of voltage infeasibility has been used to identify the buses where injection of reactive powers benefit the system most. The left eigenvector corresponding to the minimum eigenvalue gives the information about the buses responsible for voltage problem.

Consider a 2-bus power system having a generator and a load bus. The linearized relationship between voltage magnitude and reactive power injection at the load bus can be described by following equation

$$
\lambda \Delta V = \Delta Q \tag{6.11}
$$

where λ is the V-Q sensitivity obtained from the network Jacobian matrix. When λ is minimum, a small change in reactive power injection results in large voltage change.

The Jacobian matrix of N-bus power system is, in general, not a diagonal matrix. However, they can be diagonalized using modal transformation. With this technique, one obtains the following matrix relationship between modal voltages Δv $(= [T][\Delta V])$ and modal injections Δq $(= [T][\Delta Q])$, where [T] is the modal matrix of eigenvectors.

$$
\begin{bmatrix}
\lambda_1 & 0 & \dots & 0 \\
0 & \lambda_2 & \dots & 0 \\
\cdot & \cdot & \dots & \cdot \\
\cdot & \cdot & \dots & \cdot \\
\cdot & \cdot & \dots & \cdot \\
0 & 0 & \dots & \lambda_N
\end{bmatrix}
\begin{bmatrix}
\Delta v_1 \\ \Delta v_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta v_N
\end{bmatrix}
=
\begin{bmatrix}
\Delta q_1 \\ \Delta q_2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta v_N
\end{bmatrix}
\tag{6.12}
$$

The diagonal elements $\lambda_1, \ldots.., \lambda_N$ are the N-eigenvalues of the Jacobian. If one of the λ_i is very small, the modal voltage v_i becomes very sensitive to modal injection q_i while other modes remain almost unaffected. However, since several physical voltages participate to a greater or lesser degree on the modes in question, the abnormal value of the modal voltage corresponding to small eigenvalue will cause one or many physical voltages to violate their limits. The degree of participation can be determined from an inspection of entries of the left eigenvector (LEV) of the critical mode [147].

6.5 Corrective Control Action Calculation

As established in section 6.4, the optimal direction to move in parameter space to return to feasible region is associated with left eigenvector (ω^*) corresponding to minimum eigenvalue of Jacobian $[J(\mathbf{x}^*)]$ of power flow equations. The sensitivity (θ_u) of $d(\mathbf{Q})$ defined in equation (6.10) to a set of practical controls $\mathbf{u} = [u_1, u_2, \ldots, u_N]^T$ can be given [125] as

$$\theta_u^T = -\omega^* \begin{bmatrix} \frac{\partial f_{N_q+1}}{\partial u_1} & \frac{\partial f_{N_q+1}}{\partial u_2} & \cdots & \frac{\partial f_{N_q+1}}{\partial u_N} \\ \vdots & \vdots & & \vdots \\ \frac{\partial f_N}{\partial u_1} & \frac{\partial f_N}{\partial u_2} & \cdots & \frac{\partial f_N}{\partial u_N} \end{bmatrix} = -\omega^*[f_Q(\mathbf{x}^*) - Q]_u \tag{6.13}$$

where

$$f_i = [f_{Qi}(\mathbf{x}^*) - Q_i] \qquad i = N_q + 1, \ldots.., N \tag{6.14}$$

The elements of vector $\theta_{\mathbf{u}}$ provide a linear estimate of the effect of a particular control upon $d(\mathbf{Q})$. Negelecting nonlinearities, the necessary change in a single control u_i to return to the feasibility is given by

$$\Delta u_i = \frac{d(\mathbf{Q})}{\omega_i^*[\mathbf{f_Q}(\mathbf{x}^*) - \mathbf{Q}]_{u_i}} \tag{6.15}$$

for the case of reactive power injection controls, the column of the Jacobian corresponding to Q_i is unity. Thus, the equation (6.15) becomes

$$\Delta u_i = \frac{d(\mathbf{Q})}{\omega_i^*} \tag{6.16}$$

It has been observed that the change in control, obtained from equation (6.16) provides overcorrection of voltages. In the present work, through experimentation (as given in section 6.7.1), it was found that this problem can be overcome by adding reactive power residue $\Delta Q_i (= [f_{Q_i}(\mathbf{x}^*) - \mathbf{Q}_i])$ at each load bus to the left eigenvector ω_i^*. The equation (6.16) in its modified form can be written as

$$\Delta u_i = \frac{d(\mathbf{Q})}{\omega_i^* + \Delta Q_i} \tag{6.17}$$

6.6 Solution Algorithm

The proposed methodology has been applied to compute the reactive power support to achieve feasible solution. The sensitivity relationship between the change in real and reactive powers with respect to change in bus voltage magnitudes and angles is defined as

$$\begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta \mathbf{V} \end{bmatrix} \tag{6.18}$$

Although both P and Q changes affect the system voltages, it is possible to study the approximate effect of change in reactive power injections on voltage insecurity or optimal reactive power flow infeasibility by setting $\Delta P = 0$ (P constant) and deriving a Q-V sensitivity relationship,

$$[\Delta \mathbf{Q}] = [J_R][\Delta \mathbf{V}] \tag{6.19}$$

where $[J_R] = [J_4] - [J_3][J_1]^{-1}[J_2]$.

The computational steps are as follows:

Step–I: Minimize the function $F(\mathbf{V}, \delta)$ given in equation (6.4) along with constraints and obtain the corresponding voltage magnitudes $\mathbf{V}^*$ and angles δ^*.

Step–II: Calculate $d(\mathbf{Q})$ from equation (6.10). If $F(\mathbf{V}, \delta) = 0$, the optimal power flow solution is feasible and infeasible if $F(\mathbf{V}, \delta)$ in non-zero. In the later case, go to Step-III.

Step–III: Calculate the reduced matrix $[J_R]$ corresponding to the value of $\mathbf{V}^*$ and δ^* obtained in step-I.

Step–IV: Calculate the minimum eigenvalue of reduced Jacobian $[J_R]$ and obtain the corresponding left eigenvector ω^*.

Step–V: Calculate the additional controls from equation (6.17).

Step-V provides the required control action at various buses. Theoretically any of these controls should be capable of alleviating the infeasibility problem. Though this is valid on smaller system, but may not be adequate for larger systems, specially, when problematic buses are far off from the bus, where a control has been selected. In such cases more than one control can be utilized. One criteria proposed in this work for selecting the group of such controls is based on maximum reactive power residue values. The buses having higher values of residue are selected for controls. In case there are many such buses, only those buses, having lower voltage ($\mathbf{V}^*$) values, can be selected for placement of controls.

6.7 Test Results and Discussions

To establish the effectiveness of the proposed method, the studies were conducted on IEEE 14-bus, IEEE 30-bus and the practical 75-bus UPSEB systems as described in Appendices-B, C and D, respectively. A successive quadratic programming (SQP) was used to solve the minimization problem. The results of the three systems are given below.

6.7.1 IEEE 14-bus System

For this system, the results of a severe outage case of line (1-2) has been presented. The upper and lower voltage limits at all the load buses were taken as 1.10 pu and 1.0 pu, respectively. The voltage magnitudes at P-V buses were fixed to their specified values. From the load flow it was found that voltages at buses 4, 8, 9, and 14 violated the limits for the above contingency case. The function $F(\mathbf{V},\delta)$ given in equation (6.4) was minimized to determine vector $\mathbf{x}^*$. The left eigenvector corresponding to the minimum eigenvalue of reduced Jacobian was calculated. The required reactive power injection C_1 and C at each bus to alleviate the voltage violation were first calculated by using equations (6.16) and (6.17), respectively which are presented in Table 6.1. The minimum eigenvalue of reduced Jacobian and Euclidean distance were found to be 2.7228 and 0.05177, respectively.

After application of each controls taken one at a time, a load flow was run. It was observed that the control at the bus where reactive power residue (ΔQ) was higher, was more effective (in present case at bus-8). Reactive power injection at a bus away from problematic buses (e.g. at bus-14) could not improve the voltage profile of the system. The reactive power injection required at bus-8 using equations (6.16) and (6.17) are 87.89

Table 6.1: 14-bus system– Results of line (1-2) outage

Bus No.	Base Voltage	LEV ω^*	ΔQ (in pu)	x* Voltage	C MVAR	V^C (in pu)	C_1 MVAR	V^{C_1} (in pu)
1	1.060	–	–	1.060	–	1.060	–	1.060
2	1.009	–	–	1.045	–	1.045	–	1.045
3	1.035	–	–	1.070	–	1.070	–	1.070
4	0.987	–	–	1.010	–	1.000	–	1.000
5	1.071	–	–	1.090	–	1.090	–	1.090
6	1.031	0.2425	0.017	1.065	20.00	1.064	21.35	1.070
7	1.020	0.4169	0.002	1.056	12.35	1.056	12.42	1.062
8	0.983	0.0589	0.041	1.026	51.82	1.032	87.89	1.058
9	0.985	0.0914	0.019	1.025	46.89	1.027	56.44	1.039
10	1.014	0.4681	0.002	1.052	11.01	1.051	11.06	1.056
11	1.021	0.3297	0.004	1.058	15.51	1.056	15.70	1.059
12	1.020	0.1476	0.014	1.056	32.04	1.055	35.07	1.056
13	1.014	0.2046	0.009	1.051	24.24	1.050	25.30	1.051
14	0.999	0.6034	0.007	1.037	8.45	1.035	8.58	1.039

MVAR and 51.82 MVAR, respectively. The voltage magnitudes V^{C_1} and V^C at all the buses were calculated with 87.89 MVAR as well as 51.82 MVAR capacitors considered at bus-8 and results are presented in Table 6.1. From Table 6.1, it is observed that the control requirements (C_1) computed from equation (6.16) result into higher voltage profile and thus, causes over correction. However, controls (C) determined by equation (6.17) after adding the residue term in the denominator along with the left eigenvector provides acceptable voltage profile with minimum reactive power injection.

In order to validate the result, the requirement of reactive power injections were also calculated using equations (6.4) to (6.7) by considering a fictitious reactive power generator at bus-8 and 14, one at a time. A reactive power injection of 54.3 MVAR at bus-8 was found to move the system into feasible region while any amount of reactive power injection at bus-14 was unable to push the system back to feasible region.

6.7.2 IEEE 30-bus System

For this system, two most severe contingency cases were considered for the study pertaining to the outage of line (1-2) and line (2-5). The upper and lower voltage limits at all the buses except slack were taken as 1.10 pu and 0.95 pu, respectively. The slack bus voltage

was fixed to its specified value of 1.06 pu. With these voltage limits, the function $F(\mathbf{V}, \delta)$ given by equation (6.4) was minimized to obtain vector $\mathbf{x}^*$ and the left eigenvector (LEV) corresponding to the minimum eigenvalue of the reduced Jacobian $[J_R]$.

In the case of line (1-2) outage, the load flow did not converge. The corrective controls C (reactive power injections) were calculated to ensure feasible optimal operation of the system which are also presented in Table 6.2. The Euclidean distance and minimum eigenvalue of the reduced Jacobian were found to be 0.02925 and 0.49691, respectively. The maximum reactive power residue was estimated to be 0.006 pu as given in Table 6.2 which was same for several buses. However, amongst them the voltage $\mathbf{V}^*$ was minimum at bus-12 and, therefore, it was selected for placing the additional reactive power controls. The bus voltage magnitudes (V^C), after the application of 132.95 MVAR capacitor at bus-12, are also given in Table 6.2.

In order to validate the results of the proposed method, the optimization problem was also solved by considering a fictitious reactive power source at bus-12. The feasible solution was obtained with 129.34 MVAR reactive power generation as compared to 132.95 MVAR calculated by the proposed methodology.

Voltages (V^{PF}) at some buses (bus-5 and bus-12), obtained from load flow, were below the lower limit in the case of line (2-5) outage as given in Table 6.3. Voltages ($\mathbf{V}^*$) and left eigenvectors ω^* after minimizing function $F(\mathbf{V}, \delta)$ given by equation (6.4) are shown in Table 6.3. The corresponding corrective controls calculated using proposed approach are also presented in this table. The minimum eigenvalue and Euclidean distance were estimated to be 0.52896 and 0.02987, respectively. In order to establish the capability of the predicted controls, each of them were considered one at a time. The load flow result with each of the controls were obtained to see the effect on the system states. It was found that corrective control was most effective if considered at a bus having maximum reactive power residue, which was at bus-12 in the present case. The voltage $\mathbf{V}^*$ was also minimum at this bus. After placing the control (114.01 MVAR capacitor) at this bus, a load flow was run to obtain the post-corrective voltage magnitudes (V^C) at all the buses which are presented in Table 6.3.

Table 6.2: 30-bus system– Results of line (1-2) outage

Bus No.	Base Voltage	x^* Voltage	LEV ω^*	ΔQ (in pu)	C MVAR	V^C (in pu)
1		1.060	–	–	–	1.060
2	L	0.982	–	–	–	1.029
3	O	0.969	–	–	–	1.010
4	A	1.044	–	–	–	1.082
5	D	0.954	–	–	–	1.010
6		1.039	–	–	–	1.071
7	F	0.997	.0654	.006	40.97	1.039
8	L	0.983	.1186	.006	23.48	1.021
9	O	1.006	.0662	.006	40.51	1.040
10	W	1.039	.3224	.006	8.90	1.077
11		0.956	.0268	.006	89.16	0.993
12		0.950	.0160	.006	132.95	1.063
13	N	0.961	.0263	.006	90.56	1.012
14	O	0.994	.0970	.006	28.40	1.026
15	T	0.989	.1131	.006	24.56	1.021
16		0.990	.0965	.006	28.54	1.024
17		0.980	.1162	.006	23.94	1.016
18	C	0.977	.1386	.006	20.23	1.009
19	O	0.972	.1445	.006	19.44	1.004
20	N	0.975	.1419	.006	19.78	1.008
21	V	0.975	.1429	.006	19.64	1.012
22	E	0.977	.1480	.006	18.99	1.013
23	R	0.984	.1644	.006	17.17	1.016
24	G	0.983	.2093	.006	13.59	1.017
25	E	1.015	.3278	.006	8.76	1.049
26	D	1.001	.4114	.006	7.01	1.032
27		0.960	.0248	.005	98.15	0.987
28		0.966	.0556	.006	47.48	1.013
29		1.025	.4236	.006	6.81	1.058
30		1.104	.4347	.006	6.46	1.047

Table 6.3: 30-bus system– Results of line (2-5) outage

Bus No.	Base Voltage	x* Voltage	LEV ω^*	ΔQ (in pu)	C MVAR	V^C (in pu)
1	1.060	1.060	–	–	–	1.060
2	1.040	1.053	–	–	–	1.045
3	0.986	1.019	–	–	–	1.010
4	1.056	1.097	–	–	–	1.082
5	0.908	0.950	–	–	–	1.010
6	1.055	1.096	–	–	–	1.071
7	1.010	1.053	.0648	.006	42.19	1.044
8	0.994	1.041	.1174	.006	24.21	1.028
9	1.023	1.066	.0650	.006	42.07	1.048
10	1.046	1.098	.3241	.006	9.05	1.084
11	0.989	1.018	.0246	.006	97.61	1.017
12	0.937	0.976	.0162	.010	114.01	1.056
13	0.979	1.012	.0259	.006	93.64	1.019
14	1.007	1.054	.0955	.006	29.43	1.034
15	1.002	1.049	.1115	.006	25.42	1.029
16	1.003	1.049	.0951	.006	29.55	1.032
17	0.991	1.038	.1147	.006	24.74	1.024
18	0.986	1.036	.1367	.006	20.93	1.016
19	0.981	1.031	.1426	.006	20.10	1.012
20	0.983	1.033	.1401	.006	20.45	1.015
21	0.985	1.034	.1414	.006	20.26	1.019
22	0.987	1.036	.1465	.006	19.59	1.021
23	0.993	1.044	.1627	.006	17.71	1.024
24	0.991	1.043	.2079	.006	13.96	1.025
25	1.019	1.074	.3285	.006	8.93	1.056
26	1.002	1.061	.4118	.006	7.15	1.039
27	1.001	1.025	.0210	.004	119.48	1.025
28	0.982	1.018	.0557	.006	48.41	1.018
29	1.026	1.084	.4260	.006	6.91	1.066
30	1.015	1.074	.4418	.006	6.67	1.054

6.7.3 75-bus UPSEB System

For this system also several contingency cases were considered for the study. However, the result of only one contingency case corresponding to outage of line (41-74), is presented in this Chapter. The upper and lower voltage limits were taken as 1.05 pu and 0.95 pu, respectively. Slack bus voltage was fixed to its specified value of 1.03 pu. The left eigenvector and bus voltages $\mathbf{V}^*$ are given in Table 6.4.

The load flow program did not converge for the above outage case of a 400 kV line between bus-41 and bus-74. The minimum eigenvalue of reduced Jacobian and Euclidean distance were found to be 2.26401 and 0.43417, respectively. The controls predicted by the proposed method are listed in Table 6.4. It was found in this system that injecting reactive power at one bus was unable to alleviate the system infeasibility. The load flow did not converge taking a single control on any of the buses. Hence, more than one controls were sought in the present system.

The selection of the buses were based on the maximum reactive power residue. Four buses having maximum reactive power residues (buses 23, 41, 42 and 74) were first selected for reactive power injections. Only one forth of the controls (predicted by proposed method) were utilized at these buses. It was found that these controls were able to bring the system back to feasible region. However, these buses are the 400 kV buses, where it may not be practical and cost effective to install the shunt capacitors. Hence, the buses having lower residue value than the above four buses and belonging to 220 kV network (where placement of shunt capacitors are more practical) were considered. Five such buses viz. buses 24, 27, 51, 67 and 69 were selected with controls taken as one fifth of the values suggested by the proposed method. It was observed that with these controls (65.19, 58.91, 44.99, 68.00 and 64.71 MVAR capacitors at buses 24, 27, 51, 67 and 69 respectively) the system returns to the feasible region. The voltages (V^C) after placing these controls are given in Table 6.4

6.8 Conclusions

This Chapter has presented a new algorithm to decide corrective control actions required in severe contingency cases in order to enhance the security of the system. The algorithm uses the minimum Euclidean distance to quantify the infeasibility of the system and

Table 6.4: 75-bus system– Results of line (41-74) outage

Bus No.	x^* Voltage	LEV ω^*	ΔQ (in pu)	C MVAR	V^C (in pu)
1	1.030	—	—	—	1.030
2	1.044	—	—	—	1.044
3	1.044	—	—	—	1.030
4	1.043	—	—	—	1.050
5	1.027	—	—	—	1.050
6	1.027	—	—	—	1.050
7	1.037	—	—	—	1.050
8	1.032	—	—	—	1.040
9	1.049	—	—	—	1.050
10	1.029	—	—	—	1.020
11	1.036	—	—	—	1.020
12	1.036	—	—	—	1.040
13	1.037	—	—	—	1.050
14	1.044	—	—	—	1.030
15	1.022	—	—	—	1.010
16	1.029	0.0182	0.014	1348.35	1.020
17	1.031	0.0175	0.020	1157.79	1.021
18	1.026	0.0376	0.052	484.56	1.024
19	1.014	0.0512	0.047	442.13	0.995
20	1.011	0.0442	0.043	479.90	0.988
21	1.016	0.1742	0.005	242.28	1.003
22	1.030	0.1832	0.019	214.72	1.012
23	0.997	0.0672	0.100	259.67	0.981
24	1.007	0.0592	0.074	325.95	1.008
25	1.021	0.2212	0.015	183.81	1.002
26	0.995	0.0851	0.081	261.39	0.986
27	1.002	0.0764	0.071	294.55	1.006
28	1.023	0.0923	0.015	404.63	1.014
29	1.032	0.1725	0.017	229.11	1.015
30	1.018	0.1665	0.004	128.83	1.006
31	1.018	0.0760	0.045	358.82	1.036
32	1.017	0.0796	0.043	354.14	1.034
33	1.026	0.1119	0.062	249.67	1.035
34	1.003	0.0280	0.032	723.62	1.009
35	1.034	0.0163	0.019	1229.94	1.025
36	1.014	0.0432	0.039	528.19	0.994
37	0.996	0.0464	0.044	480.28	0.974

Contd. ...

Table 6.4. (Contd.) ...

Bus No.	$\mathbf{x}^*$ Voltage	LEV ω^*	ΔQ (in pu)	C MVAR	V^C (in pu)
38	1.040	0.1734	0.005	243.23	1.027
39	1.021	0.1387	0.040	242.96	1.024
40	1.015	0.0242	0.032	772.54	0.994
41	0.996	0.0110	0.194	211.79	1.022
42	0.997	0.0108	0.192	214.09	1.024
43	1.029	0.0990	0.006	413.50	1.017
44	1.035	0.0268	0.036	691.35	1.019
45	1.044	0.0397	0.033	597.21	0.984
46	0.991	0.0302	0.014	982.29	0.977
47	1.017	0.0456	0.055	431.58	1.003
48	0.999	0.0282	0.023	847.99	0.977
49	0.989	0.0293	0.022	846.36	0.966
50	1.003	0.0360	0.041	563.86	0.990
51	1.005	0.1290	0.064	224.96	1.032
52	1.012	0.1519	0.052	212.93	1.033
53	1.012	0.1705	0.003	250.24	1.004
54	1.010	0.0680	0.047	377.54	1.001
55	0.999	0.0495	0.051	432.01	0.981
56	1.021	0.1190	0.008	341.87	1.010
57	1.002	0.1695	0.017	232.80	0.994
58	1.006	0.1548	0.019	249.81	0.996
59	1.001	0.1704	0.029	217.74	0.996
60	1.009	0.2784	0.013	148.99	0.987
61	1.010	0.1615	0.006	259.21	1.006
62	1.008	0.1184	0.027	298.60	1.018
63	1.004	0.0607	0.056	372.04	0.988
64	0.999	0.0574	0.058	376.23	0.970
65	1.015	0.1736	0.005	243.10	1.003
66	1.003	0.0531	0.039	471.41	0.977
67	1.008	0.0577	0.070	340.00	1.011
68	1.017	0.0474	0.064	389.74	1.026
69	0.977	0.0562	0.078	323.53	0.950
70	1.009	0.4179	0.004	102.91	0.985
71	1.002	0.0715	0.065	318.07	1.005
72	1.010	0.3754	0.008	113.24	0.987
73	1.040	0.0452	0.043	492.26	0.985
74	0.994	0.0661	0.106	252.28	0.978
75	1.034	0.1746	0.016	227.79	1.017

computes the reactive power injection(s) required to move the system from infeasible to feasible region. The test results on IEEE 14-bus, IEEE 30-bus and 75-bus UPSEB systems demonstrate the following:

(i) The proposed method can be effectively used for corrective control action (VAR) planning to ensure feasible optimal operation or secure operation of the system.

(ii) The application of controls at the buses having larger reactive power residue (ΔQ) are more effective. If the maximum residue value ΔQ is same at more than one bus, the control at a bus having lowest voltage ($\mathbf{V}^*$) should be selected.

(iii) The proposed method can also be used to select more than one controls which are required in larger systems to bring it into feasible region.

Chapter 7

Conclusions

7.1 General

Modern power utilities are being equipped with computer aided energy management system in order to ensure the secure and economic operation of the system. The network security analysis and optimization forms an important part of advanced application softwares in modern energy management systems. There has been continued interest in developing simple and efficient models for these problems. This thesis has addressed to certain aspects of voltage security analysis, optimization and controls. The main contributions of the thesis include the development of new models for

- linearized load flow for voltage contingency analysis reported in Chapter 2,
- distribution factors for fast post-outage calculations of voltages and reactive power output of sources reported in Chapter 3,
- voltage and reactive power performance indices including optimal weight adjustment for voltage contingency selection reported in Chapter 4,
- genetic algorithm based loss minimization technique for both real and reactive power dispatch reported in Chapter 5, and
- corrective control action planning to enhance the voltage/reactive power security of the system given in Chapter 6.

The aim of this Chapter is to highlight the main findings of the work carried out in this thesis and making suggestions for further research work in this vital area of voltage security and loss minimization studies.

7.2 Summary of Important Findings

In *Chapter 2,* six new models of linearized load flow have been developed which can be utilized to compute voltage magnitudes at the load buses with acceptable accuracy for base case as well as contingency cases. The concept of minimization of least square error and integral square error have been used, probably for the first time, in linearizing the power flow equations over the possible operating range. Five different versions (models A_1 to A_5) have been developed based on integral square error minimization and the sixth version (model-B) using the least square error minimization principles. From the test results obtained in IEEE 14-bus, IEEE 30-bus and 75-bus UPSEB systems presented in this chapter the following conclusions are drawn:

(i) Amongst the six proposed linearized versions, the versions A_1, A_2 and A_3 provide significantly accurate results as compared to those obtained with the first iteration of Newton-Raphson load flow (in polar coordinates).

(ii) The version A_3 in polar coordinates, provides the most accurate results amongst all the linearized versions tried out in the prediction of bus voltages. The error is less than 5.0 % even in severe contingency cases. The model-B is found to be the least accurate.

(iii) The proposed linearized models are non-iterative in nature and takes approximately same CPU time as the one iteration of Newton-Raphson load flow method.

(iv) For some of the contingency cases, where AC load flow methods diverge and do not provide the post-outage results, the proposed method is able to predict the approximate values of post-outage bus voltage magnitudes.

(v) Hence, the proposed linearized load flow models, specially version A_3, can be effectively used for the voltage contingency analysis.

In *Chapter 3*, eight new sets of voltage and reactive power distribution factors, for both line and generator outages, have been developed which can be derived directly from a

base load flow results using network sensitivity information. The test results obtained on the 14-bus, 30-bus and 75-bus systems provide following conclusions:

(i) The prediction of the post-outage bus voltages using the new distribution factors are quite accurate. However, with the use of distribution factors, the error in predicting the reactive power output of sources is slightly higher.

(ii) Since the distribution factors are obtained directly from a base load flow result, without involving any additional load flow for simulation of outages, its calculation and updating is quite fast and can be applied to on-line monitoring of voltage security of the system at control centers.

(iii) The sets of distribution factors computed at a base loading are able to predict the post-outage voltages of the system accurately even for small change in system loading. Thus, they need not be recomputed for small deviation in the loading. This further reduces the computational time for the voltage contingency analysis.

(iv) The proposed distribution factors method defined with respect to both pre-outage real and reactive powers of the elements, predicts the post-outage voltages of the system more accurately than those predicted by the distribution factors [118, 138] defined in terms of only reactive powers under different loading conditions.

(v) The proposed distribution factors compute the bus voltages with slightly less accuracy as compared to the linearized load flow models suggested in Chapter 2. However, the post-outage calculations using distribution factors are much faster as compared to the linearized load flows.

Chapter 4 has explored suitability of few voltage as well as reactive power performance indices voltage/reactive power contingency selection. A simple approach to find out optimal weights of the performance indices have been suggested. The study results on the three systems reveal the following:

(i) Use of higher order exponents for both voltage and reactive power performance indices eliminates the masking effect. Performance indices of order 10 or more (exponent $n \geq 5$) are recommended to overcome the masking problem.

(ii) The performance indices computed by the distribution factors method using optimal weights minimizes the misranking effects.

(iii) The optimal weights calculated on a base case loading can be effectively used to define the performance indices for small change in system loading conditions.

(iv) For voltage contingency selection, the voltage performance indices, in general, has provided better results as compared to the reactive power performance indices. Hence, the voltage performance indices are recommended to be used for the voltage contingency selection.

Chapter 5 has investigated a new optimal power flow model for both real and reactive power dispatch considering loss minimization as objective. The genetic algorithm (GA) has been applied, probably for the first time, for solving the complete optimal power flow problem. Investigations on the three systems provide the following:

(i) The proposed genetic algorithm based optimal power flow results into substantial reduction in system transmission loss in all the three systems and is capable of handling the system constraints effectively in its model.

(ii) The reduction in system real power transmission loss, using the proposed genetic algorithm based loss minimization model, is significantly more as compared to those obtained with only reactive power rescheduling [138]. The loss value is even lesser than those obtained with the Fletcher's quadratic programming method.

(iii) In some utilities, specially in Indian systems, where the cost characteristic of the generators are normally not available, the present optimal power flow model is more relevant and can be used for rescheduling of both real and reactive power outputs of the sources.

(iv) The loss minimization results, if implemented, will result into considerable annual saving in the energy, thus offering economic benefit and also enhance the load delivery capacity of the system.

Chapter 6 has presented a new algorithm to decide corrective control actions in contingency cases in order to enhance the security of the system. The algorithm uses the minimum Euclidean distance to quantify the infeasibility of the system and computes the reactive power injection(s), based on the eigenvalue analysis, required to move the system from infeasible to feasible region. The test results on the three systems demonstrate the following:

(i) The proposed method can be effectively used for corrective control action (VAR) planning to ensure feasible optimal operation or secure operation of the system.

(ii) The application of controls at a bus having largest reactive power residue (ΔQ) is more effective. If the maximum residue value ΔQ is same at more than one bus, the control at a bus having lowest voltage ($\mathbf{V}^*$) should be selected.

(iii) The proposed method can also be used to select more than one controls which are required in larger systems to bring it into feasible region.

7.3 Scope For Future Research

As a consequence of the investigations carried out in this thesis on development of few models for the linearized load flow and distribution factors for contingency selection, performance indices for voltage contingency ranking, loss minimization for both real and reactive power dispatch and corrective action planning to enhance the voltage security, following aspects are identified for future research work in this area.

(i) In Chapter 2, the calculation of voltage angles from linearized load flow were found to be quite inaccurate. In order to increase the accuracy of calculation of voltage angles and hence making the linearized load flow models suitable for power calculation, angles can be first computed by one iteration of the fast decoupled load flow and then linearized model can be used to predict the voltage magnitudes.

(ii) The distribution factors suggested in Chapter 3 have been calculated only for single contingency cases. A suitable algorithm can be developed for modification in the distribution factors and the model to account for the multiple contingency cases.

(iii) Some of the practical constraints such as limits on the transformer taps and line flows have not been considered for solving the optimal power flow problem using genetic algorithm in Chapter 5. These constraints can be included in the model. More work is required to evolve an effective way to handle the functional inequalities in the genetic algorithm.

(iv) The present study of optimal power flow using genetic algorithm has been conducted with the conventional serial implementation of the problem which takes more CPU

time. In order to fully exploit the benefit of genetic algorithm, its parallel implementation may be tried out.

(v) This thesis has only addressed to the static security analysis The work can be extended to consider the dynamic security aspects.

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Appendix A

The Fundamental Theorem of Genetic Algorithm

The theoretical foundations of genetic algorithm (GA) rely on a binary string representation of solutions, and on the notion of a schema (template) allowing exploration of similarities among chromosomes. The fundamental theorem is known as schema theorem which has been constructed by Holland [15] to demonstrate the information processing and convergence powers of a GA, and has come to serve as the central theorem of GA for almost a decade. The schema theorem explains how a balance between the exploration of new regions in the solution space and exploitation of those good regions that were already discovered, is realized by a GA implicitly through the use of the operators.

A schema is built by introducing a don't care symbol (*) into the alphabet of genes. A schema represents all strings (a hyper plane or subset of the search space), which matches it on all positions other than '*'. For example schema (*111100100) matches two strings (0111100100), (1111100100) and the schema (*1*1100100) matches four strings (0101100100), (01111100100), (1101100100), (1111100100)

It is clear that every schema matches exactly 2^r strings where r is number of don't care symbols '*' in a schema template. On the other hand each string of length m is matched by 2^m schemata. There are two important schema properties: *order* and *defining length.* The schema theorem will be formulated on the basis of these properties.

The *order* of the schema S (denoted by $O(S)$) is the total number of 0 and 1 present in schema, which is equal to the length of the template minus the number of don't care (*) symbols. The order defines the speciality of a schema. The notion of the order of a

schema is useful in calculating survival probabilities of the schema for mutations.

The *defining length* of the schema S (denoted by $\delta(S)$) is the distance between the first and the last fixed string positions. It defines the compactness of information contained in a schema. The notion of the defining length of a schema is useful in calculating survival probabilties of the schema for crossovers. For example, the following three schemata, each of length 10,

$$\begin{aligned} S_1 &= (***001*110) \\ S_2 &= (****00**0*) \\ S_3 &= (11101**001) \end{aligned}$$

have the following orders

$$O(S_1) = 6, O(S_2) = 3, O(S_3) = 8$$

and the following defining lengths

$$\delta(S_1) = 10 - 4 = 6, \delta(S_2) = 9 - 5 = 4 \text{ and} \delta(S_3) = 10 - 1 = 9.$$

The number of strings in a population at the time t matched by schema S can be denoted by $\zeta(S,t)$. The fitness of schema at time t ($F_e(S,t)$) is defined as the average fitness of all strings in the population matched by schema S. If p strings ($C_{i1} \ldots C_{ip}$) in population are matched by schema S, then

$$F_e(S,t) = \sum_{j=1}^{p} \frac{F_e(C_{ij})}{p} \tag{A.1}$$

After the selection step, $\zeta(S,t+1)$ strings are expected to match by schema S. Since

(i) for an average string matched by a schema S, the probability of its selection (in a single string selection) is equal to $F_e(S,t)/F(t)$ (where $F(t)$ is total fitness of the whole population at time t),

(ii) the number of string matched by schema S is $\zeta(S,t)$, and

(iii) the total number of single string selection is the number of population size (n).

It is clear that

$$\zeta(S,t+1) = \zeta(S,t).n.\frac{F_e(S,t)}{F(t)} \tag{A.2}$$

$$= \zeta(S,t)\frac{F_e(S,t)}{\bar{F}(t)} \tag{A.3}$$

where $\bar{F}(t)$ ($= F(t)/n$) is average fitness of population. If fitness of schema S is above the average fitness of population, then ratio $\frac{F_e(S,t)}{\bar{F}(t)} > 1$. This implies that expected number of

representative of schema S in population grows with generation. Equivalently, schemata with above (below) average fitness of population will receive increasing (decreasing) number of samples under selection operation.

The effect of other genetic operators, namely, crossover and mutation on survival of a schema depend on three factors : defining length of schema, order of schema and probability of operators.

A.1 Effect of Crossover

The survival of a schema S under this operator depends on defining length $\delta(S)$. Assume that the crossover site m is chosen randomly. This means any of $m-1$ positions of string belonging to a schema S can be selected with equal probabilities. The probability of destruction of a schema S is

$$p_d(S) = \frac{\delta(S)}{m-1} \tag{A.4}$$

and consequently, the probability of schema survival is

$$p_s(S) = 1 - \frac{\delta(S)}{m-1} \tag{A.5}$$

Since only some chromosomes undergo crossover with probability P_c, the probability of survival of a schema can be given by

$$p_s(S) = 1 - P_c\frac{\delta(S)}{m-1} \tag{A.6}$$

Even if a crossover site is selected between fixed position in a schema, there is a still chance for the schema to survive [111]. Hence

$$p_s(S) \geq 1 - P_c\frac{\delta(S)}{m-1} \tag{A.7}$$

A.2 Effect of Mutation

Since the probability of the alteration of a single bit is P_m, the probability of a single bit survival is $1 - P_m$. A single mutation is independent of other mutations, so probability of a schema S surviving a mutation is

$$p_s(S) = (1 - P_m)^{O(S)} \tag{A.8}$$

Since $P_m << 1$, this probability can be approximated by

$$p_s(S) \cong (1 - 0(S).P_m) \tag{A.9}$$

The combined effect of selection, crossover and mutation gives a new form of reproductive schema growth equation.

$$\zeta(S, t+1) \geq \zeta(S,t)\frac{F_e(S,t)}{\bar{F}(t)}[1 - P_c\frac{\delta(S)}{m-1} - O(S)P_m] \tag{A.10}$$

This is known as schema theorem.

Appendix B

Data For IEEE 14-Bus Test System (At 100 MVA Base)

The IEEE-14 bus system is shown in Fig. B.1. The system data is taken from reference [44] and buses renumbered. The relevant data are provided in following tables.

Table B.1: Generator Bus Data

Bus No.	Scheduled real power generation P_G(MW)	Specified Voltage magnitude Vspec. (p.u.)	Load	
			Real (MW)	Reactive (MVAR)
1(slack)	—	1.060	00.00	00.00
2	040.0	1.045	21.70	12.70
3	020.0	1.070	11.20	07.50
4	—	1.010	94.20	19.00
5	—	1.090	00.00	00.00

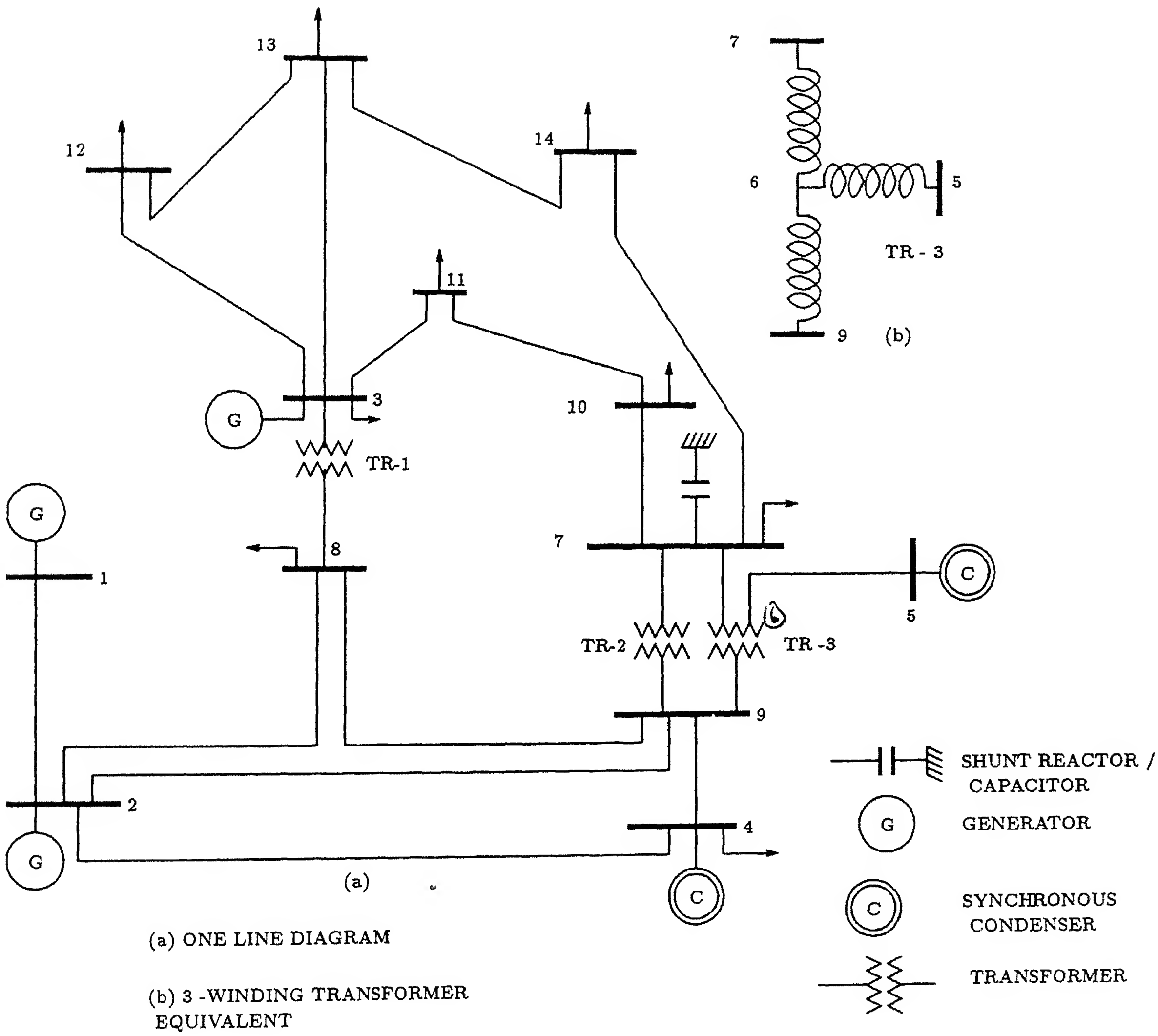

Figure B.1: IEEE 14-bus system

Table B.2: Generator Data

Gen. no.	Real power generation limit		Reactive power generation limit		Cost characteristics*		
	Maximum (MW)	Minimum (MW)	Maximum (MVAR)	Minimum (MVAR)	a_i ($/MW²-hr)	b_i ($/MW-hr)	c_i ($/hr)
1	200.0	050.0	100.0	−45.0	1.0	2.45	105.00
2	100.0	020.0	050.0	−40.0	1.0	3.51	044.40
3	100.0	020.0	024.0	−06.0	1.0	3.89	040.60
4	—	—	040.0	000.0	—	—	—
5	—	—	024.0	−06.0	—	—	—

⋆ Fuel cost of i^{th} gen. unit $F_i = (\frac{1}{2}a_i P_{G_i}^2 + b_i P_{G_i} + c_i)\$/\mathrm{hr}$

Table B.3: Load Bus Data

Bus No.	Load		External shunt susceptance(p.u.)
	Real (MW)	Reactive (MVAR)	
6	00.0	00.0	00.00
7	29.5	16.6	−0.19
8	07.6	01.6	00.00
9	47.8	−3.9	00.00
10	09.0	05.8	00.00
11	03.5	01.8	00.00
12	06.1	01.6	00.00
13	13.5	05.8	00.00
14	14.9	05.0	00.00

Table B.4: Transformer Data

Line no.	From bus	To bus	Series impedance		Tap settings
			Resistance (p.u.)	Reactance (p.u.)	
1	8	3	0.0000	0.25202	0.962
2	9	6	0.0000	0.20912	0.978
3	9	7	0.0000	0.55618	0.969

Table B.5: Line Data

Line no.	From bus	To bus	Series impedence		Shunt susceptance $\frac{1}{2}$B(p.u.)
			Resistance (p.u.)	Reactance (p.u.)	
4	1	8	0.05403	0.22304	0.0246
5	2	8	0.05695	0.17388	0.0170
6	4	9	0.06701	0.17103	0.0173
7	9	8	0.01335	0.04211	0.0064
8	1	2	0.01938	0.05917	0.0264
9	2	4	0.04699	0.19797	0.0219
10	6	5	0.00000	0.17615	0.0000
11	2	9	0.05811	0.17632	0.0187
12	6	7	0.00000	0.11001	0.0000
13	7	10	0.03181	0.08450	0.0000
14	3	11	0.09498	0.19890	0.0000
15	3	12	0.12291	0.25581	0.0000
16	3	13	0.06615	0.13027	0.0000
17	7	14	0.12711	0.27038	0.0000
18	10	11	0.08205	0.19207	0.0000
18	12	13	0.22092	0.19988	0.0000
20	13	14	0.17093	0.34802	0.0000

Appendix C

Data For IEEE 30-Bus Test System (At 100 MVA Base)

The IEEE-30 bus system is shown in Fig. C.1. The system data is taken from reference [44] and buses renumbered. The relevant data are provided in following tables.

Table C.1: Generator Bus Data

Bus No.	Scheduled real power generation P_G(MW)	Specified Voltage magnitude Vspec. (p.u.)	Load	
			Real (MW)	Reactive (MVAR)
1(slack)	—	1.060	00.00	00.00
2	040.0	1.045	21.70	12.70
3	020.0	1.010	00.00	30.00
4	—	1.082	30.00	00.00
5	—	1.010	09.42	19.00
6	—	1.071	00.00	00.00

Table C.2: Generator Data

Gen. no.	Real generation limit		React. generation limit		Cost characteristics*		
	Maximum (MW)	Minimum (MW)	Maximum (MVAR)	Minimum (MVAR)	a_i ($/MW²-hr)	b_i ($/MW-hr)	c_i ($/hr)
1	300.0	050.0	150.0	−100.0	1.0	2.45	105.00
2	150.0	020.0	050.0	−40.0	1.0	3.51	044.40
3	150.0	020.0	040.0	−10.0	1.0	3.89	040.60
4	—	—	024.0	−06.0	—	—	—
5	—	—	040.0	−40.0	—	—	—
6	—	—	024.0	−06.0	—	—	—

Table C.3: Load Bus Data

Bus No.	Load		External shunt susceptance(p.u.)
	Real(MW)	Reactive(MVAR)	
7	00.0	00.0	0.00
8	05.8	02.0	0.00
9	11.2	07.5	0.00
10	00.0	−0.0	0.19
11	07.6	01.6	0.00
12	22.8	10.9	0.00
13	00.0	00.0	0.00
14	06.2	01.6	0.00
15	08.2	02.5	0.00
16	03.5	01.8	0.00
17	09.0	05.8	0.00
18	03.2	00.9	0.00
19	09.5	03.4	0.00
20	02.2	00.7	0.00
21	17.5	11.2	0.00
22	00.0	00.0	0.00
23	03.2	01.6	0.00
24	08.7	06.7	0.043
25	00.0	00.0	0.00
26	03.5	02.3	0.00
27	02.4	01.2	0.00
28	00.0	00.0	0.00
29	02.4	00.9	0.00
30	10.6	01.9	0.00

Table C.4: Transformer Data

Line no.	From bus	To bus	Series impedance		Tap settings
			Resistance (p.u.)	Reactance (p.u.)	
1	13	07	0.0000	0.2080	0.978
2	13	08	0.0000	0.5560	0.969
3	11	09	0.0000	0.2560	0.962
4	28	10	0.0000	0.3960	0.968

Table C.5: Line Data

Line no.	From bus	To bus	Series impedence		Shunt susceptance
			Resistance (p.u.)	Reactance (p.u.)	$\frac{1}{2}$B(p.u.)
5	2	5	0.0472	0.1983	0.0209
6	2	13	0.0581	0.1763	0.0187
7	11	13	0.0119	0.0414	0.0045
8	5	12	0.0460	0.1160	0.0102
9	13	12	0.0267	0.0820	0.0085
10	13	3	0.0120	0.0420	0.0045
11	1	2	0.0192	0.0575	0.0264
12	1	27	0.0452	0.1852	0.0204
13	7	8	0.0000	0.1100	0.0000
14	2	11	0.0570	0.1737	0.0184
15	9	14	0.1231	0.2559	0.0000
16	9	15	0.0662	0.1304	0.0000
17	9	16	0.0945	0.1987	0.0000
18	14	15	0.2210	0.1997	0.0000
19	16	17	0.0824	0.1923	0.0000
20	15	18	0.1070	0.2185	0.0000
21	18	19	0.0639	0.1292	0.0000
22	19	20	0.0340	0.0680	0.0000
23	8	20	0.0936	0.2090	0.0000
24	8	17	0.0324	0.0845	0.0000
25	8	21	0.0348	0.0749	0.0000
26	8	22	0.0727	0.1499	0.0000
27	21	22	0.0116	0.0236	0.0000
28	15	23	0.1000	0.2020	0.0000
29	22	24	0.1150	0.1790	0.0000
30	23	24	0.1320	0.2700	0.0000
31	24	25	0.1885	0.3292	0.0000
32	25	26	0.2544	0.3800	0.0000
33	25	10	0.1093	0.2087	0.0000
34	27	11	0.0132	0.0379	0.0042
35	10	29	0.2198	0.4153	0.0000
36	10	30	0.3202	0.6027	0.0000
37	29	30	0.2399	0.4533	0.0000
38	3	28	0.0636	0.2000	0.0214
39	13	28	0.0169	0.0599	0.0065
40	9	6	0.0000	0.1400	0.0000
41	7	4	0.0000	0.2080	0.0000

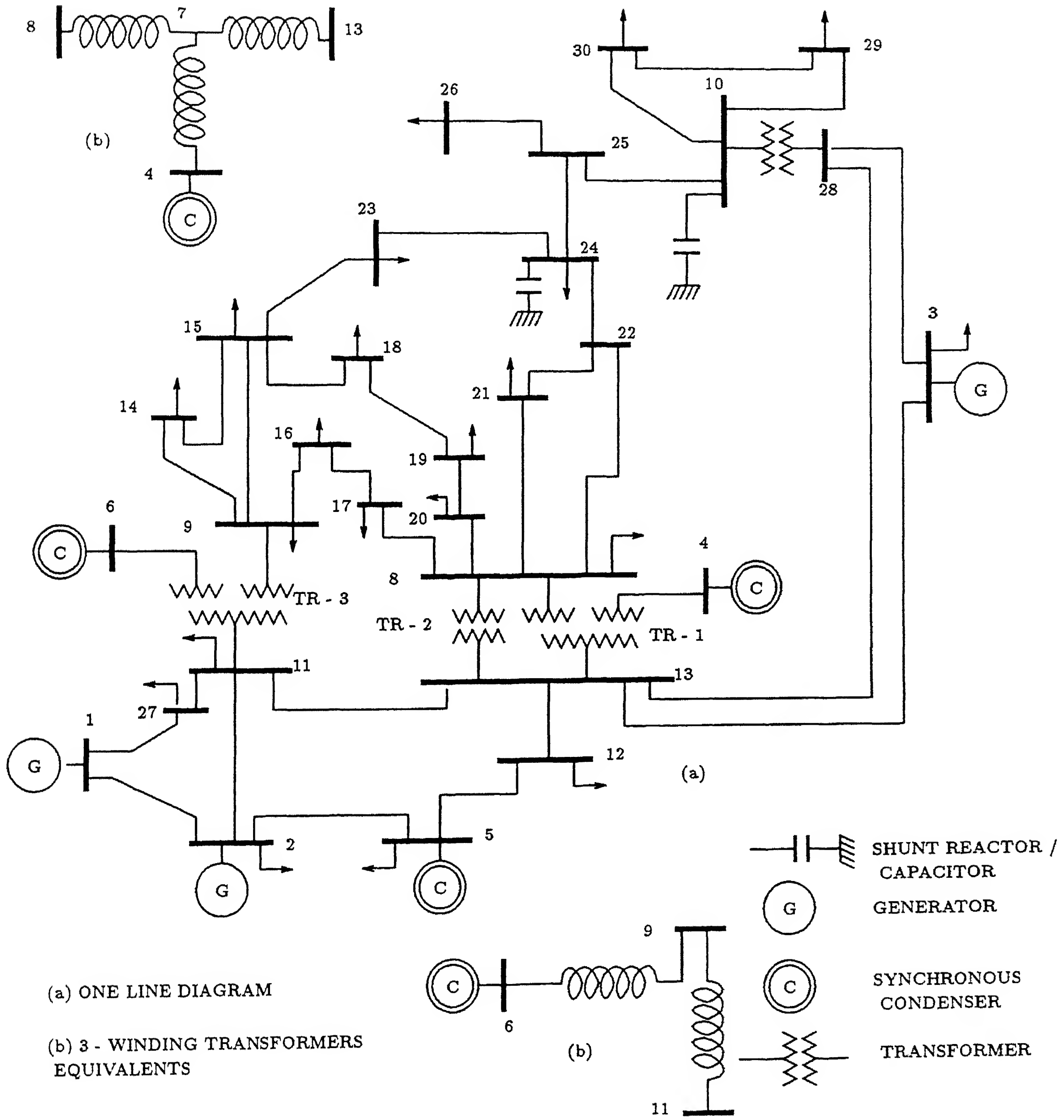

Figure C.1: IEEE 30-bus system

Appendix D

Data For 75-Bus UPSEB Test System (At 100 MVA Base)

The 75-bus UPSEB system is shown in Fig. D.1. The system data is taken from U.P. State Electricity Borad and buses are renumbered. The relevant data are provided in following tables.

Table D.1: Generator Data

Bus No.	Scheduled real power gen. P_G(MW)	Specified Voltage magnitude Vspec. (p.u.)	Real power limits		Reactive power limits	
			Maximum (MW)	Minimum (MW)	maximum (MVAR)	Minimum (MVAR)
1(slack)	—	1.030	900.0	100.0	400.0	0.0
2	260.0	1.030	300.0	100.0	96.0	0.0
3	180.0	1.050	200.0	40.0	83.0	0.0
4	100.0	1.030	170.0	40.0	60.0	0.0
5	180.0	1.050	240.0	00.0	31.0	0.0
6	120.0	1.050	120.0	00.0	20.0	0.0
7	060.0	1.050	100.0	00.0	19.0	0.0
8	080.0	1.050	100.0	20.0	68.0	0.0
9	550.0	1.050	570.0	60.0	250.0	0.0
10	080.0	1.020	120.0	30.0	56.0	0.0
11	109.0	1.020	200.0	40.0	105.0	0.0
12	1800.0	1.050	1800.0	1800.0	344.0	0.0
13	900.0	1.050	900.0	900.0	280.0	0.0
14	150.0	1.030	150.0	150.0	84.0	0.0
15	454.0	1.010	454.0	454.0	35.0	-30.0

Table D.2: Load Bus Data

Bus No.	Load		Line Reactors in(MVAR)
	Real(MW)	Reactive(MVAR)	
16	-58 69	27.56	
17	0.00	0.00	100.0
19	0.00	0.00	50.0
20	156.37	33.93	
22	0.00	0.00	50.0
23	0.00	0.00	100.0
24	227.95	40.53	
25	210.48	43.43	
26	0.00	0.00	163.0
27	306.00	40.70	
28	127.75	28.35	
29	0.00	0.00	100.0
30	226.46	44.24	
32	78.11	11.59	
34	81.70	83.84	
35	0.00	0.00	50.0
36	0.00	0.00	50.0
37	144.28	40.93	
39	85.12	29.46	
41	0.00	0.00	223.0
42	1000.0	0.0	63.0
46	156.32	83.36	
47	74.55	8.77	
48	50.83	13.97	
49	85.72	51.58	
50	202.10	74.94	
51	57.76	0.62	
52	98.27	-18.15	
53	82.63	-0.33	
54	161.95	29.00	
55	274.23	31.08	
56	140.28	34.32	
57	152.78	18.53	
58	94.19	11.29	
59	121.89	11.01	
60	74.20	7.42	
61	106.50	6.58	
62	100.18	18.13	
63	58.01	5.31	
64	56.79	13.33	

Table . . . Contd.

ble D.2 (Contd.) ...

Bus No.	Load Real(MW)	Load Reactive(MVAR)	Line Reactors in(MVAR)
65	147.84	12.81	
66	31.74	15.18	
67	96.43	10.55	
68	42.87	33.60	
69	55.94	32.53	
70	23.34	2.30	
71	91.73	21.36	
72	52.52	11.76	
73	477.0	00.0	50.0
74	288.0	0.0	283.0
75	-444.0	0.0	

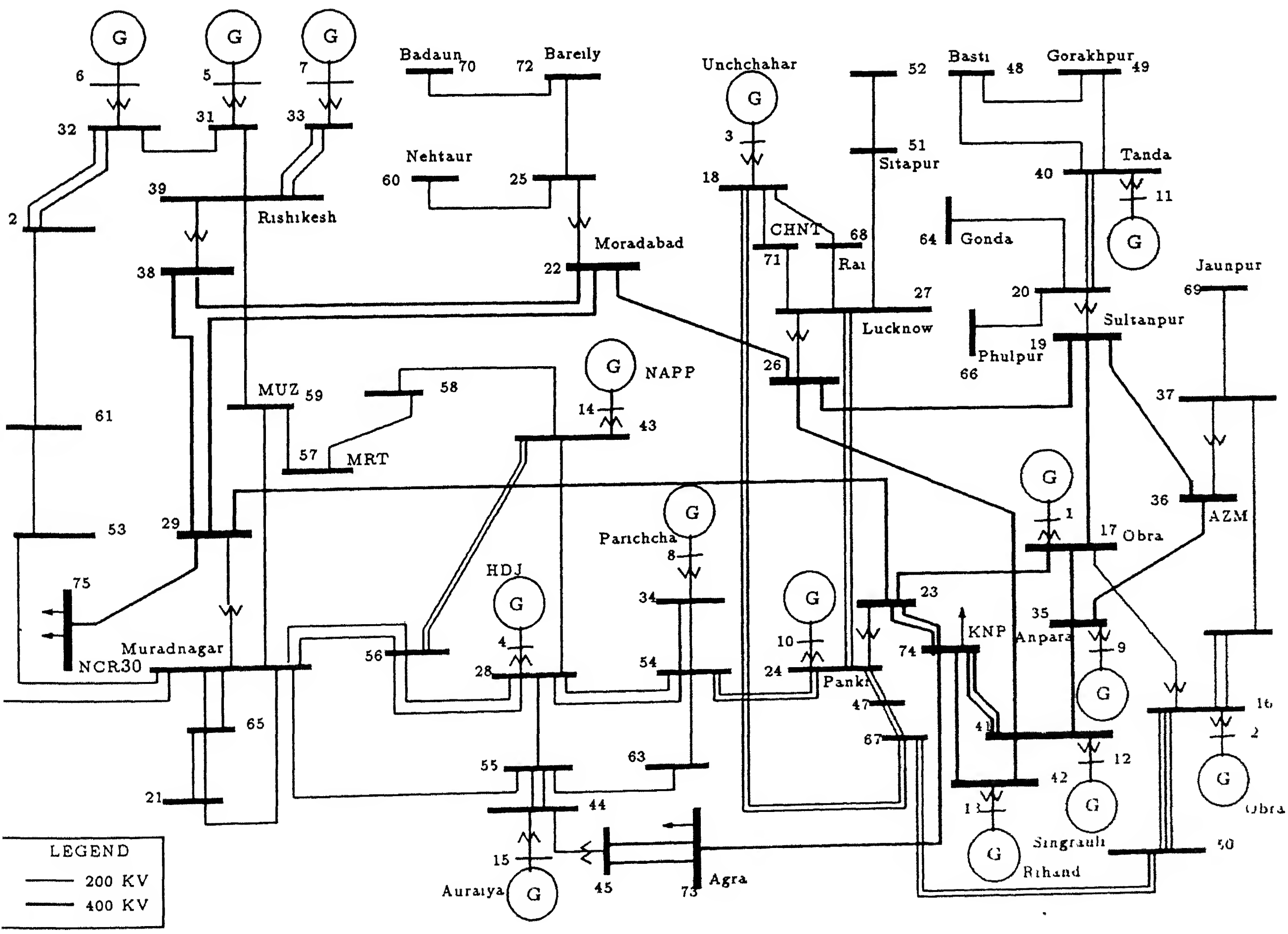

Figure D.1: 75-bus UPSEB system

Table D.3: Transformer Data

Line no.	From bus	To bus	Series impedance Resistance (p.u.)	Reactance (p.u.)	Tap settings
1	17	1	.00073	.01460	1.000
2	16	2	.00123	.02469	1.000
3	18	3	.00000	.02917	1.000
4	28	4	.00306	.06135	1.000
5	31	5	.00235	.04710	1.000
6	32	6	.00514	.10285	1.000
7	33	7	.00549	.10978	1.000
8	34	8	.00000	.04860	1.000
9	35	9	.00049	.01943	1.000
10	24	10	.00243	.04860	1.000
11	40	11	.00770	.02720	1.000
12	41	12	.00016	.00591	1.000
13	42	13	.00030	.01199	1.000
14	43	14	.00000	.02841	1.000
15	44	15	.00000	.02273	1.000
16	19	20	.00130	.05208	1.000
17	19	20	.00130	.05208	1.000
18	17	16	.00065	.02604	1.000
19	22	25	.00130	.05208	1.000
20	22	25	.00130	.05208	1.000
21	23	24	.00130	.05200	1.000
22	23	24	.00130	.05200	1.000
23	26	27	.00130	.05200	1.000
24	26	27	.00130	.05200	1.000
25	29	30	.00129	.05208	1.000
26	29	30	.00129	.05208	1.000
27	29	30	.00129	.05208	1.000
28	36	37	.00130	.05208	1.000
29	36	37	.00130	.05208	1.000
30	38	39	.00130	.05208	1.000
31	45	44	.00112	.04444	1.000
32	45	44	.00112	.04444	1.000

Table D.4: Line Data

Line no.	From bus	To bus	Series impedence		Shunt susceptance
			Resistance (p.u.)	Reactance (p.u.)	$\frac{1}{2}$B (p.u.)
33	16	46	.01620	.07760	.07015
34	16	46	.01620	.07760	.07015
35	16	50	.02979	.14238	.12881
36	16	50	.02979	.14238	.12881
37	16	50	.02979	.14238	.12881
38	17	19	.00468	.04770	.62450
39	17	23	.00785	.07990	1.04738
40	19	26	.00294	.02997	.39206
41	47	50	.01093	.05221	.18892
42	47	67	.00662	.03164	.11451
43	24	27	.00505	.02416	.08730
44	24	54	.02582	.12342	.11164
45	24	54	.02582	.12342	.11164
46	25	43	.01270	.06410	.05220
47	54	28	.01060	.05060	.18320
48	28	43	.00580	.02900	.02370
49	28	56	.00370	.01780	.06440
50	56	30	.00490	.02370	.08590
51	30	57	.00750	.03840	.03110
52	53	30	.00679	.03412	.02782
53	53	61	.00666	.03390	.02672
54	30	61	.01440	.07310	.05850
55	57	58	.00670	.03390	.02670
56	57	59	.00583	.02956	.02346
57	59	39	.01410	.07180	.05700
58	39	31	.01440	.07250	.05900
59	54	63	.00990	.05090	.04010
60	55	63	.00780	.03980	.03140
61	61	62	.01160	.05830	.04750
62	62	32	.01380	.07000	.0563
63	62	32	.01380	.07000	.0563
64	35	36	.00479	.04880	.63614
65	46	37	.01732	.08784	.06973
66	19	36	.00254	.02584	.33798
67	17	35	.00051	.00517	.06760
68	40	48	.00830	.04240	.03340
69	74	41	.00927	.09429	1.23293
70	74	41	.00833	.08478	1.10855
71	26	41	.00823	.08375	1.09503
72	48	49	.00930	.04750	.03740

Table D.4 (Contd.) ...

Line no.	From bus	To bus	Series impedence		Shunt susceptance
			Resistance (p.u.)	Reactance (p.u.)	$\frac{1}{2}$B (p.u.)
73	49	40	.01330	.06680	.05420
74	38	29	.00370	.03762	.48870
75	38	22	.00325	.03307	.43264
76	18	47	.00437	.02552	.09399
77	30	65	.00248	.01186	.04294
78	41	42	.00031	.00310	.04056
79	42	74	.00918	.09306	1.21680
80	23	74	.00015	.00155	.02704
81	24	67	.00124	.00593	.02147
82	18	68	.00336	.01963	.01808
83	18	71	.01344	.07852	.07230
84	27	68	.01344	.07852	.07230
85	27	71	.00336	.01963	.01808
86	43	58	.01315	.06696	.05278
87	43	56	.00499	.02397	.08523
88	55	44	.01996	.09588	.08523
89	55	44	.01996	.09588	.08523
90	73	45	.00121	.01109	.72815
91	29	22	.00260	.02646	.34610
92	21	65	.00083	.00396	.01431
93	34	54	.03540	.17020	.15130
94	34	54	.03540	.17020	.15130
95	39	33	.01410	.07180	.05700
96	39	33	.01410	.07180	.05700
97	31	32	.00050	.00253	.00805
98	20	40	.01160	.05880	.04710
99	20	40	.01160	.05880	.04710
100	21	30	.00695	.03500	.02843
101	28	55	.01998	.10127	.08051
102	35	41	.00031	.00310	.04056
103	37	69	.01212	.06100	.04956
104	25	60	.01660	.08430	.06720
105	51	52	.01550	.07940	.06300
106	20	64	.01830	.09270	.07390
107	70	72	.00878	.04430	.03580
108	20	66	.01325	.06667	.05416
109	29	75	.00051	.00517	.06760
110	26	22	.00650	.06617	.86521
111	23	29	.00806	.08169	1.06808
112	74	73	.00559	.05686	.74354
113	25	72	.01598	.08108	.06436
114	27	51	.01600	.08100	.06440

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1	High School	U.P. Board	1980	70.8%	Science Group
2	Intermediate	U.P. Board	1982	67.4%	Science Group
3	B.Tech.	KNIT Sultanpur	1987	82.87%	Electrical Engg.
4	M. Tech.	I.I.T. Kanpur	1989	CPI=10.0	Electrical(Power systems)

Employment Record

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U. P. State Electricity Board	Assistant Engineer	08/08/88 to date	System Design & Development Studies (Planning)

Research Papers (Published/Accepted)

(1) *Novel Non-Iterative Load Flow for Voltage Contingency,* International Journal of Electrical Power & Energy System, Vol. 16, No. 1, pp 11-16, 1994.

(2) *Analysis of Distribution Losses of Lucknow City,* published in Journal of The Society of Power Engineers (INDIA), Vol. 40 No. 3 & 4 , pp 10-15, July/Oct. 1992.

(3) *Optimal Reactive Power Dispatch Using Genetic Algorithms,* Proc of IEEE sponsored Third International Symposium of Electricity Distribution and Energy Management (ISEDEM'93) , Singapore, October 27-29, 1993, pp 484-489.

(4) *Voltage and Reactive Power Distribution Factors for line, Transformer & Generator Outage Studies,* Proc. of IEE sponsored International Conference on Advances in Power System Control, Operation and Management, Hong-Kong, December 7-10, 1993, pp 794-800.

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(7) *Optimal Reactive Power Dispatch using New Loss Formula,* published in 59th R & D session of CBIP (India) at Calcutta during Feb. 1-4, 1994, pp 114-118.

(8) *Power System Studies for Expansion Planning,* published in the Conference on 'T & D Losses' organized by Power Finance Corporation of India and USAID during January 21-22 1994, Vol. III, E-2, pp 1-8.

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(11) Discussion to the paper by M. Noroozíaan and G. Anderson, *Power Flow Control by use of Controllable series Component,* IEEE Trans. on Power Delivery, Vol 8 No. 3, pp 1420-1429, July 1993.

(12) Discussion of IEEE paper # 94WM 064-6 PWRD titled *Damping Of Power System Oscillations by Use of Controllable Components,* IEEE Trans. on Power Delivery, Vol-9, No.4, pp 2046-2054, November 1994.

(13) Discussion of IEEE paper # 93SM515-7PWRS titled *A Generation Rescheduling Method to Increase the Dynamic Security of Power System,* IEEE T-PWRS to appear.

(14) Discussion of IEEE paper # 94 WM 245-1 PWRS titled *Computation of a Practical Method to Restore Power Flow Solvability,* IEEE T-PWRS to appear.

(15) Discussion of IEEE paper # 94 WM 219-6-PWRS titled *Static Security in Power System Operation in Fuzzy Real Load Conditions,* IEEE T-PWRS to appear.

(16) Discussion of IEEE paper # 94 SM 535-5 PWRS titled *Parallel Implementation of Power System Transient Stability Analysis,* IEEE T-PWRS to appear.

(17) Discussion of IEEE paper # 94 SM 537-1 PWRS titled *A Hybrid Tool to Assist the Operator in Reactive Power/Voltage Control and Optimization,* IEEE T-PWRS to appear.

(18) Discussion of IEEE paper # 94 SM 578-5 PWRS titled *Effects of Load Dynamics on Power System Damping,* IEEE T-PWRS to appear.

(19) Discussion of IEEE paper # 94 SM 514-0 PWRS titled *New Methods for Computing a Saddle Node Bifurcation Point for Voltage Stability Analysis,* IEEE T-PWRS to appear.

(20) Discussion of IEEE paper # 94 SM 578-5 PWRS titled *On Bifurcation, Voltage Collapse And Load Modeling,* IEEE T-PWRS to appear.

(21) *Corrective action Planning to Achieve feasible Optimal Load Flow Solution,* submitted for publication in the Proc. of IEE , Part-C, Transmission and distribution.

(22) *Performance Study of GTO Inverters in HVDC Link,* submitted for publication in Journal of Electic Power Systems Research, USA.

(23) *Reactive Power Planning to achieve Secure Operation of Power System,* submitted for publication in 60th Diamond jubilee R & D session of CBIP, New Delhi.